Übung 2 – Elektronische Schaltungen (ES)

Sommersemester 2020

Bipolartransistoren

INSTITUT FÜR HOCHFREQUENZTECHNIK UND ELEKTRONIK

EINFÜHRUNG

- Großsignalersatzschaltbild und Arbeitspunkt-Bestimmung
- Kleinsignalersatzschaltbild
- Grundschaltungen

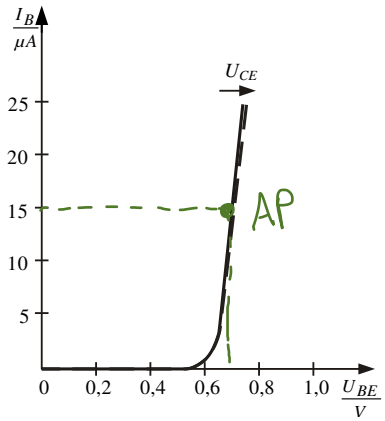
Großsignalanalyse

- Nichtlineare Analyse
- Allgemeingültige Beschreibung des Transistorverhaltens

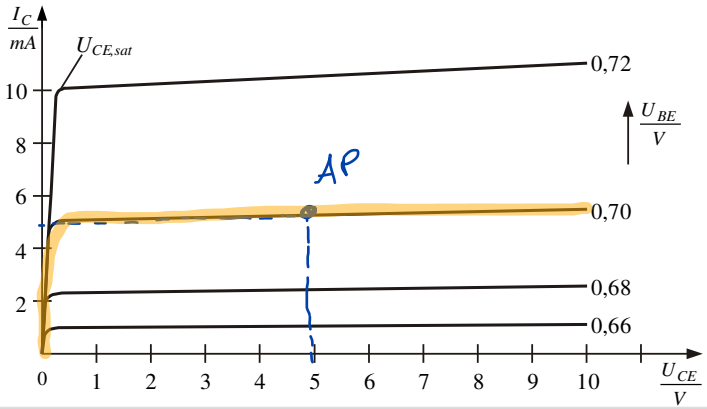
Arbeitspunkt:

- Charakterisiert durch: I_B, U_{BE}, I_C, U_{CE}
- Festgelegt durch: äußere Beschaltung
- Ziel: maximale Aussteuerbarkeit

Eingangskennlinienfeld



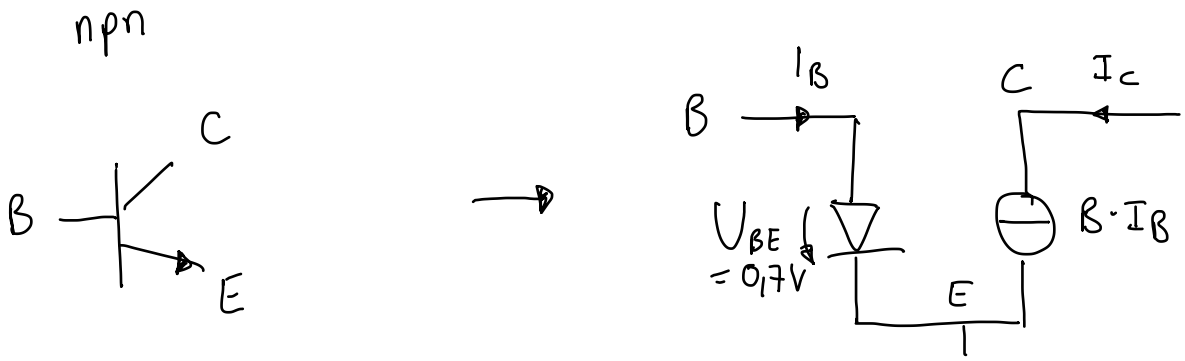
Ausgangskennlinienfeld



Großsignalanalyse

Großsignalersatzschaltbild:

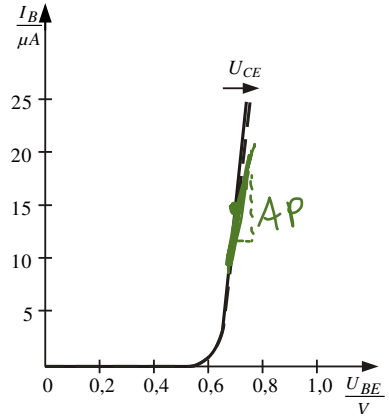
- Hilft dabei den Arbeitspunkt zu berechnen
- Gleichspannungen und –ströme werden betrachtet → Kondensatoren verhalten sich wie ein Leerlauf
- Vereinfachung des Transistors:



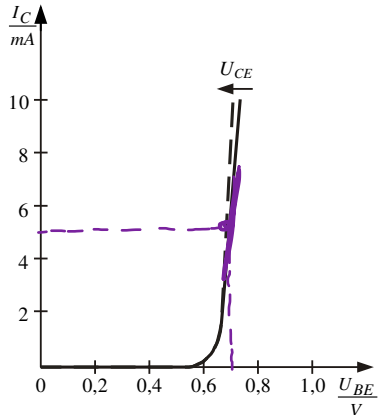
Kleinsignalanalyse

- Lineare Analyse
- Beschreibung nur gültig für kleine Auslenkungen um den Arbeitspunkt
  → kleine Wechselspannung

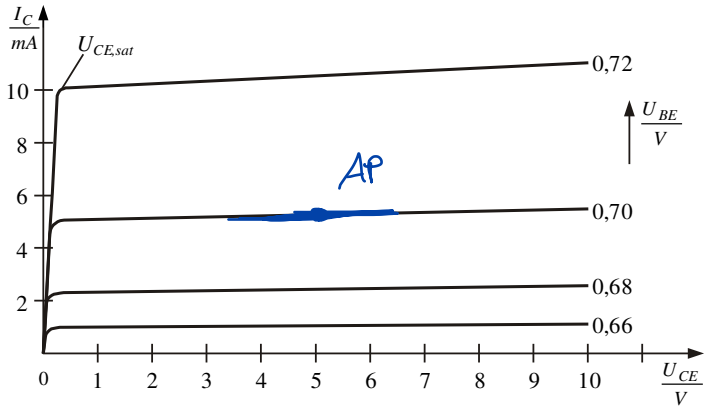
Übertragungskennlinie



$$\frac{\partial I_B}{\partial U_{BE}} = \frac{1}{r_{BE}}$$



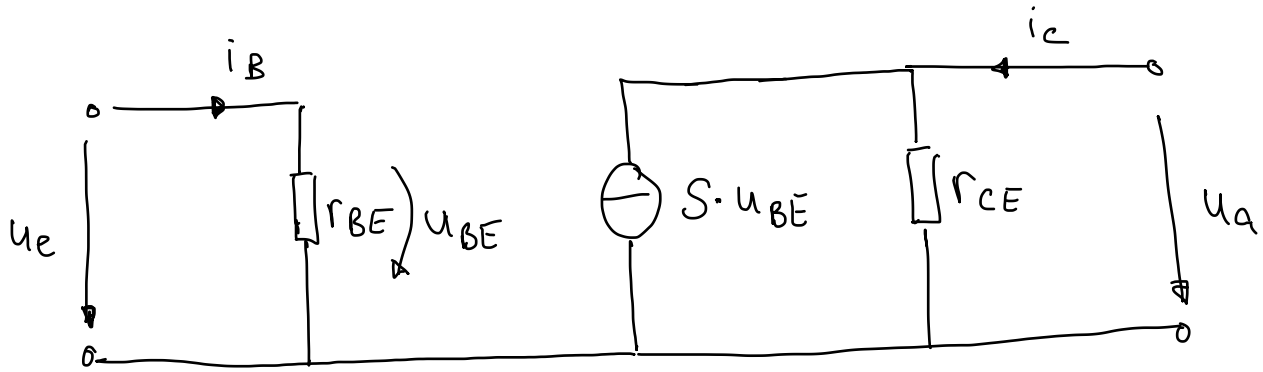
$$\frac{\partial I_C}{\partial U_{BE}} = S$$



$$\frac{\partial I_C}{\partial U_{CE}} = \frac{1}{r_{CE}}$$

Kleinsignalanalyse

Kleinsignalersatzschaltbild:



$$i_B = \frac{1}{r_{BE}} \cdot u_{BE}$$

$$i_C = S \cdot u_{BE} + \frac{1}{r_{CE}} \cdot u_{CE}$$

Kleinsignalanalyse

- Kondensatoren verhalten sich wie ein Kurzschluss
- Berechnung von: $S, r_{\mathrm{BE}}, r_{\mathrm{e}}, r_{\mathrm{a}}, A$, $r_{CE} \to \infty$

Bipolartransistor

Hinweis: Spannungsverstärkung und Ausgangswiderstand gelten bei Leerlauf am Ausgang!

Steilheit:

$$S = \frac{\partial I_{\mathrm{C}}}{\partial U_{\mathrm{BE}}} = \frac{I_{\mathrm{C,A}}}{U_T}$$

Kleinsignal-Eingangs-Widerstand:

$$r_{\mathrm{BE}} = \frac{\beta}{S}$$

a) Emitterschaltung

Kleinsignal-Spannungsverstärkung:

$$A = -S \cdot R_{\mathrm{C}}$$

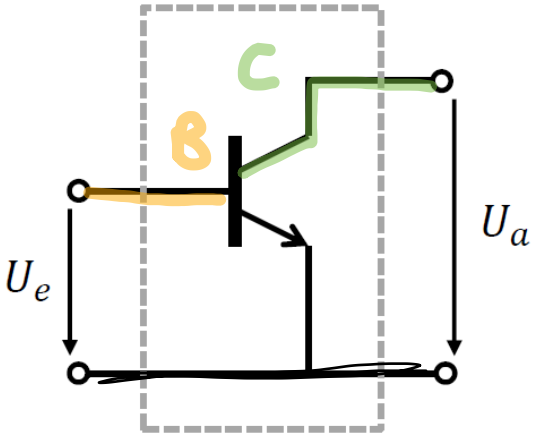
Kleinsignal-Eingangswiderstand:

$$r_{\mathrm{e}} = \left.\frac{\partial u_{\mathrm{e}}}{\partial i_{\mathrm{e}}}\right|_A = r_{\mathrm{BE}}$$

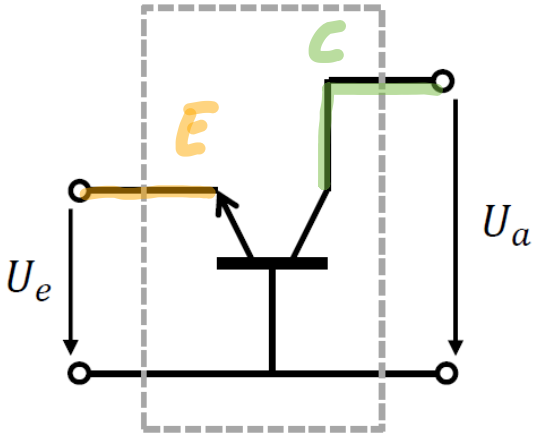
Kleinsignal-Ausgangswiderstand:

$$r_{\mathrm{a}} = \left.\frac{\partial u_{\mathrm{a}}}{\partial i_{\mathrm{a}}}\right|_A = R_{\mathrm{C}}$$

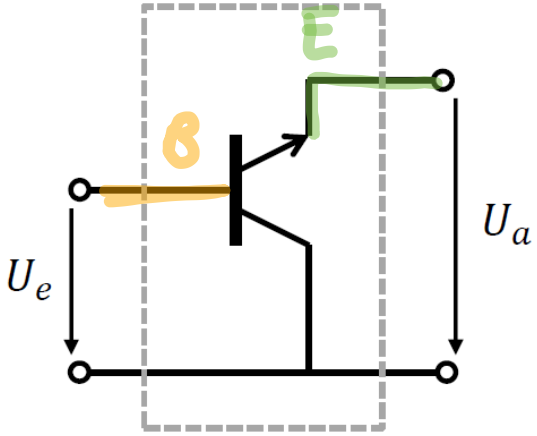
Grundschaltungen



Emitterschaltung



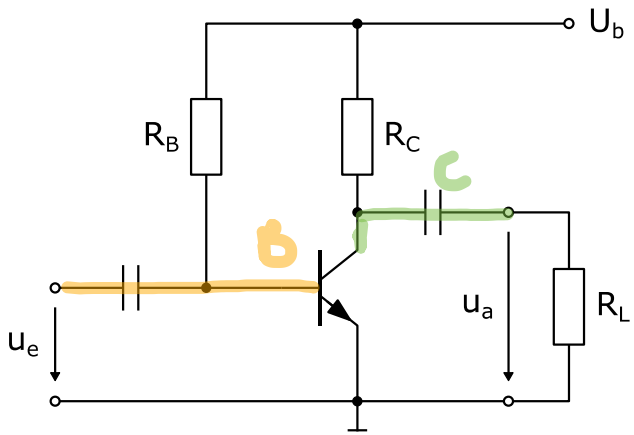
Basisschaltung



Kollektorschaltung

Aufgabe 1

a) ges: Grundschaltung

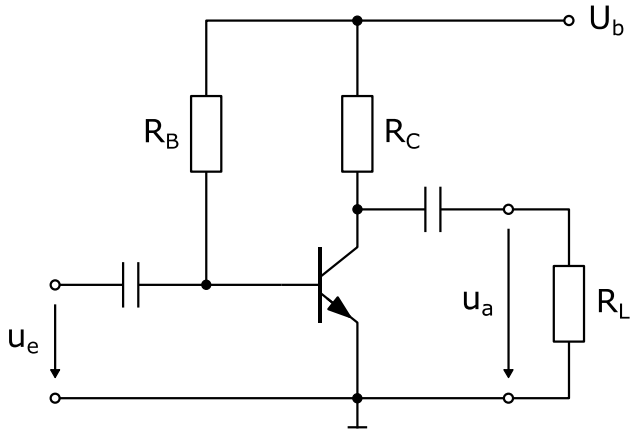


Emitterschaltung

$R_B = 470\ \text{k}\Omega$
$R_C = 1{,}6\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 24\ \text{V}$
$B = \beta = 150$

Aufgabe 1

b) ges: Aufgabe der Kondensatoren

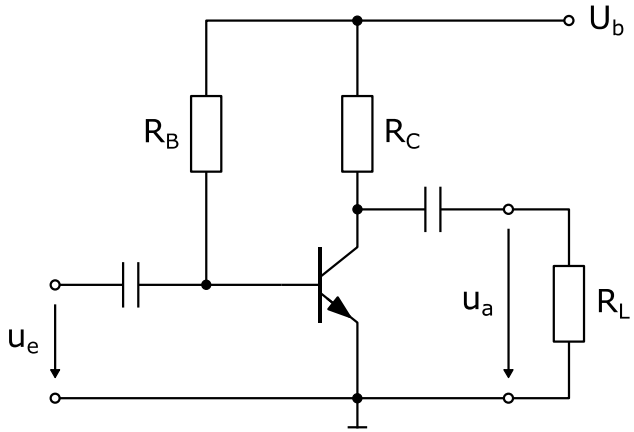


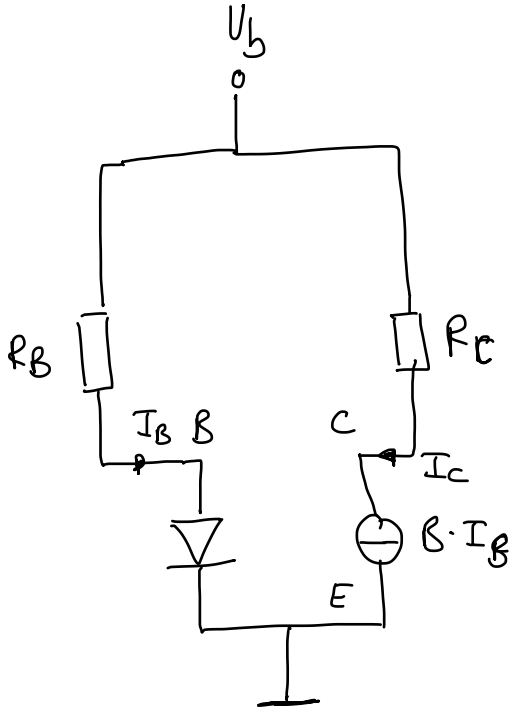
Gleichspannungsanteile von U_{BE} & U_{CE} werden vom Ein- & Ausgang entkoppelt.

$$R_B = 470\ \text{k}\Omega$$
$$R_C = 1{,}6\ \text{k}\Omega$$
$$R_L = 4{,}7\ \text{k}\Omega$$
$$U_b = 24\ \text{V}$$
$$B = \beta = 150$$

Aufgabe 1

c) ges: Großsignalersatzschaltbild

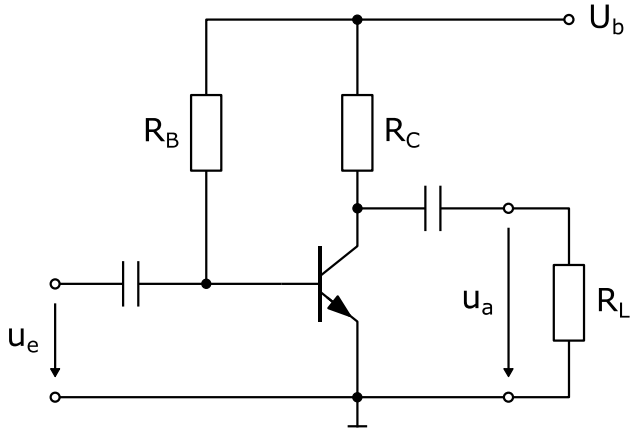




$$R_\mathrm{B} = 470\ \mathrm{k\Omega}$$
$$R_\mathrm{C} = 1{,}6\ \mathrm{k\Omega}$$
$$R_\mathrm{L} = 4{,}7\ \mathrm{k\Omega}$$
$$U_\mathrm{b} = 24\ \mathrm{V}$$
$$\mathrm{B} = \beta = 150$$

Aufgabe 1

d) ges: I_B, I_C, U_{CE}, S



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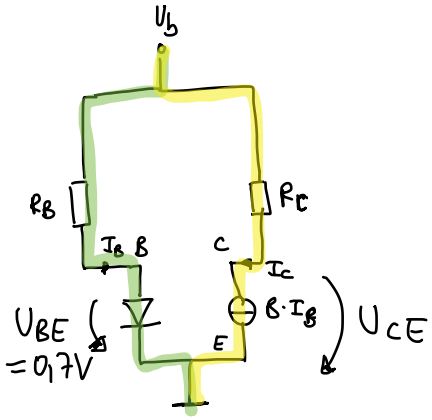
$U_b = 24\ \text{V}$
$B = \beta = 150$



$U_b = I_B \cdot R_B + U_{BE} \rightarrow I_B = \frac{U_b - U_{BE}}{R_B} = \frac{24\,\text{V} - 0{,}7\,\text{V}}{470\,\text{k}\Omega} = 49{,}6\ \mu\text{A}$

$I_C = B \cdot I_B = 150 \cdot 49{,}6\,\mu\text{A} = 7{,}44\,\text{mA}$

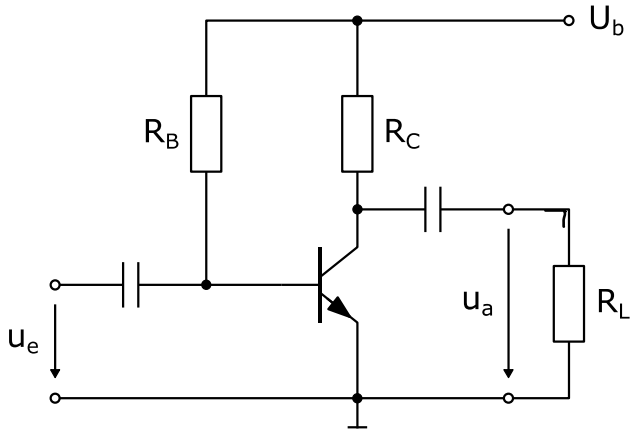
$U_{CE} = U_b - I_C \cdot R_C = 24\,\text{V} - 7{,}44\,\text{mA} \cdot 1{,}6\,\text{k}\Omega = 12{,}1\,\text{V}$

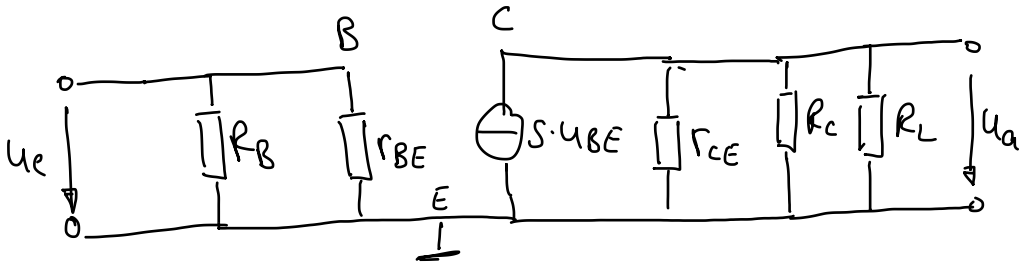
$S = \frac{I_C}{U_T} = \frac{\partial I_C}{\partial U_{BE}} = \frac{7{,}44\,\text{mA}}{26\,\text{mV}} = 286{,}1\,\text{mS}$

$U_T = \frac{k_B T}{e}$

Aufgabe 1

e) ges: Kleinsignalersatzschaltbild





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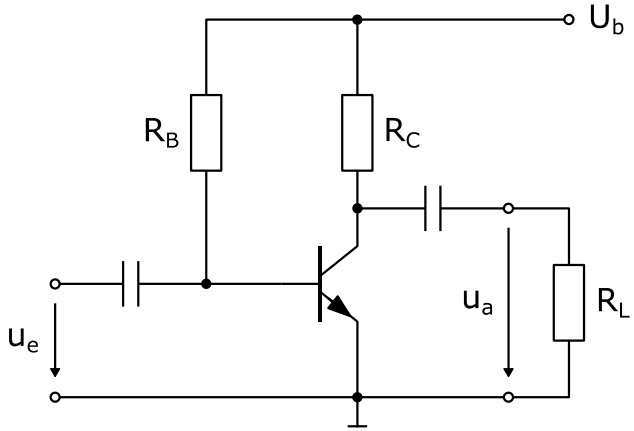
$$R_\mathrm{C} = 1{,}6\ \mathrm{k\Omega}$$
$$R_\mathrm{L} = 4{,}7\ \mathrm{k\Omega}$$
$$U_\mathrm{b} = 24\ \mathrm{V}$$
$$\mathrm{B} = \beta = 150$$

Aufgabe 1

f) ges: r_e, r_a, A



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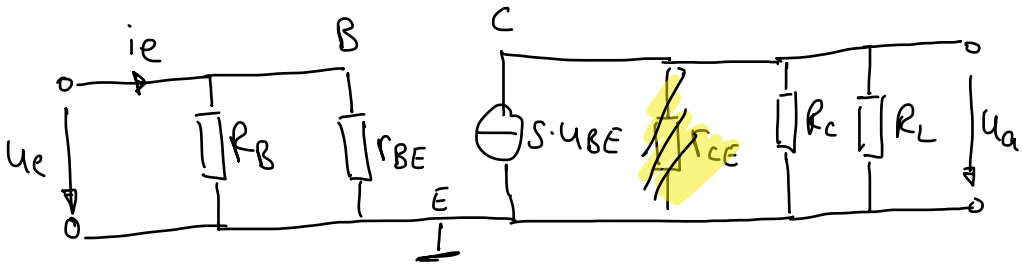
$U_b = 24\ \text{V}$
$B = \beta = 150$



$$r_e = \frac{u_e}{i_e} = R_B \parallel r_{BE} = \frac{R_B \cdot r_{BE}}{R_B + r_{BE}} = 524\,\Omega \approx r_{BE}$$

$$\hookrightarrow \frac{\beta}{S} = 524{,}3\,\Omega$$

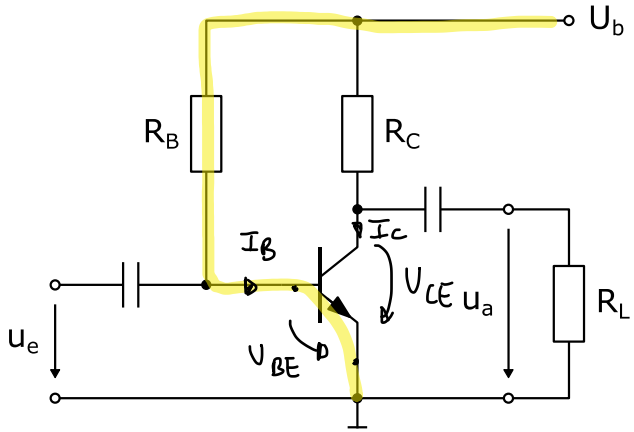
$$r_a = r_{CE} \parallel R_C \parallel R_L = \frac{R_C \cdot R_L}{R_C + R_L} = 1{,}19\,\text{k}\Omega$$

($r_{CE} \to \infty$)

$$A = \frac{u_a}{u_e} = -S \cdot r_a = -286{,}1\,\text{mS} \cdot 1{,}19\,\text{k}\Omega = -341{,}5$$

Aufgabe 1

g) geg: neues $B_{neu} = \beta = 300$



$R_B = 470\ \text{k}\Omega$
$R_C = 1{,}6\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 24\ \text{V}$
$B = \beta = 150$

1. R_B austauschen

2. $U_b = R_B \cdot I_{B,neu} + 0{,}7\text{V}$

$$R_{B_{neu}} = \frac{U_b - 0{,}7\text{V}}{I_{B,neu}}$$

$$I_{B,neu} = \frac{I_c}{B_{neu}} = \frac{7{,}44\text{mA}}{300} = 24{,}8\,\mu\text{A}$$

$$R_{B,neu} = \frac{24\text{V} - 0{,}7\text{V}}{24{,}8\,\mu\text{A}} = 939{,}5\,\text{k}\Omega$$

$R_{B,neu} = 910\ \text{k}\Omega$

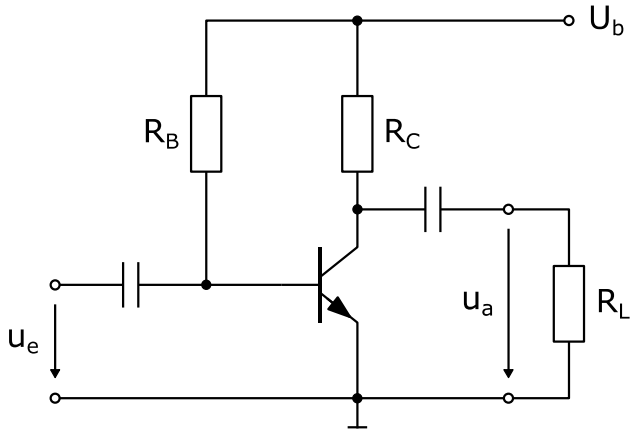
Aus Formelsammlung

E 24 – Reihe

1,0	1,1	1,2	1,3	1,5	1,6	1,8	2,0	2,2	2,4	2,7
3,0	3,3	3,6	3,9	4,3	4,7	5,1	5,6	6,2	6,8	7,5
8,2	9,1									

Aufgabe 1

g) geg: neues $B = \beta = 300$



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$R_C = 1{,}6\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 24\ \text{V}$
$B = \beta = 150$

3. Neuer AP

$U_b = I_B \cdot R_B + U_{BE} \rightarrow I_{B,neu} = \frac{U_b - U_{BE}}{R_{B,neu}} = \frac{24\,V - 0{,}7\,V}{910\,k\Omega} = 25{,}6\,\mu A$

$I_{C,neu} = B \cdot I_B = 300 \cdot 25{,}6\,\mu A = 7{,}68\,mA$

$U_{CE} = U_b - I_C \cdot R_C = 24\,V - 7{,}68\,mA \cdot 1{,}6\,k\Omega$
$= 11{,}71\,V$

$S = \frac{I_C}{U_T} = \frac{\partial I_C}{\partial U_{BE}} = \frac{7{,}68\ mA}{26\ mV} = 295\,mS$

$U_T = \frac{k_B T}{e}$

$A_{neu} = -S \cdot R_C \,||\, R_L = -295\,mS \cdot 1{,}19\,k\Omega$
$= -351$

Exkurs - Stromverstärkung

In Lehrbüchern

- Großsignalstromverstärkung B

$$\mathrm{B} = \frac{I_\mathrm{C}}{I_\mathrm{B}}$$

- Kleinsignalstromverstärkung β

$$\beta = \left.\frac{\partial I_\mathrm{C}}{\partial I_\mathrm{B}}\right|_{U_\mathrm{CE}=0}$$

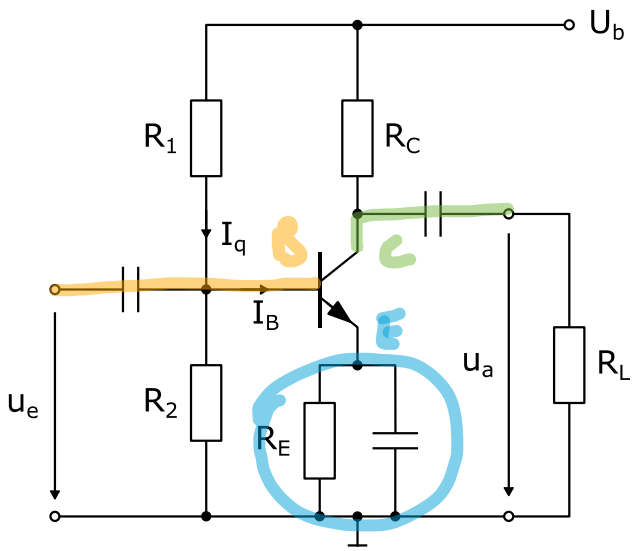
In Datenblättern

- DC current gain h_FE
- Small signal current gain h_fe
- 2-Tor Messung: Hybrid-Parameter:

$$u_{BE} = h_{11} i_B + h_{12} u_{CE}$$
$$i_C = h_{21} i_B + h_{22} u_{CE}$$

Aufgabe 2

a) ges: Grundschaltung



$$R_2 = 1{,}8\ \text{k}\Omega$$
$$R_\text{E} = 1{,}1\ \text{k}\Omega$$
$$U_\text{b} = 15\ \text{V}$$
$$U_\text{BE,on} = 0{,}7\ \text{V}$$
$$I_\text{C} = 2\ \text{mA}$$
$$U_\text{CE} = 5\ \text{V}$$

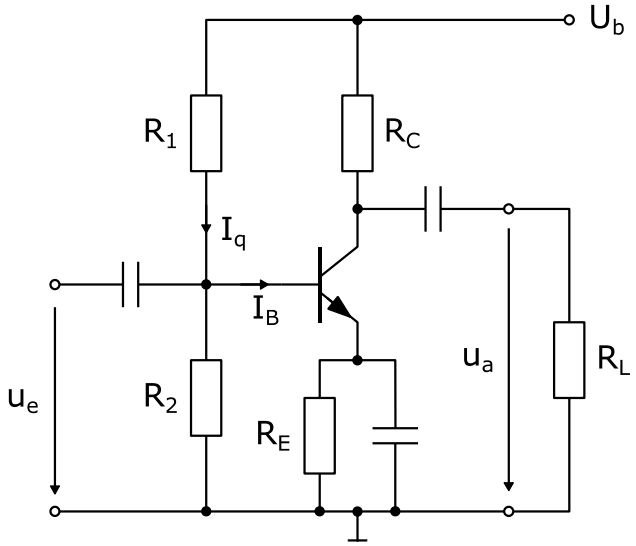
Emitterschaltung

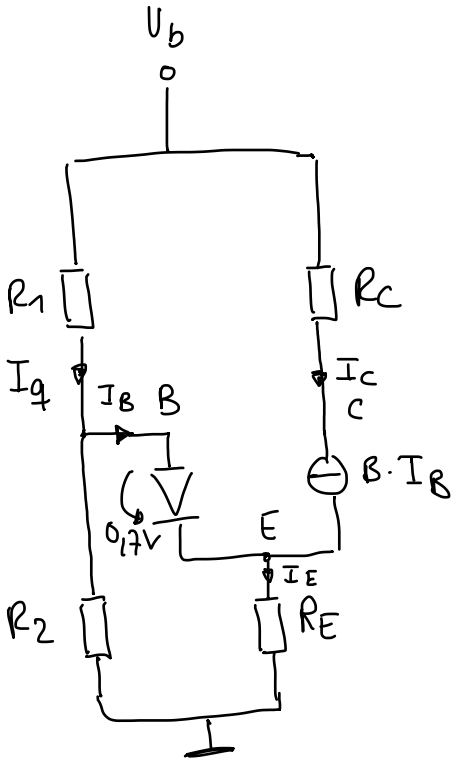
Großsignal: mit Stromgegenkopplung

Kleinsignal: Emitterschaltung

Aufgabe 2

b) ges: Großsignalersatzschaltbild





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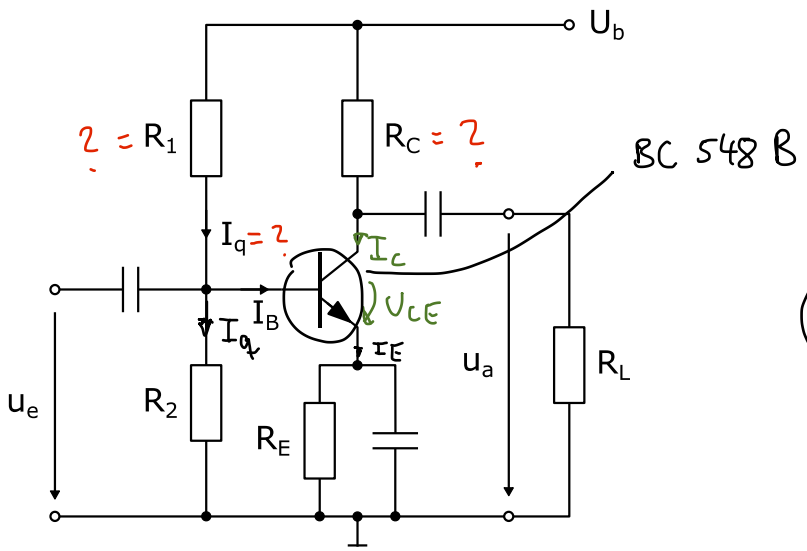
Aufgabe 2

c) ges: R_1, I_q



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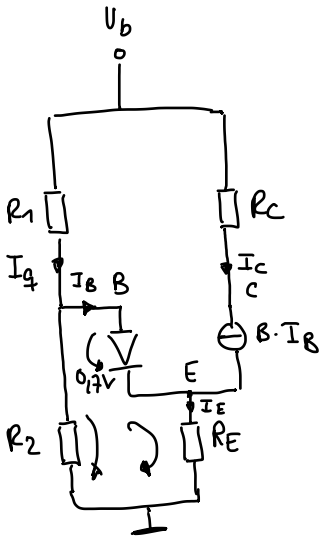
$U_b = 15\ \mathrm{V}$
$U_{BE,on} = 0{,}7\ \mathrm{V}$
$I_C = 2\ \mathrm{mA}$
$U_{CE} = 5\ \mathrm{V}$

$I_B \ll I_q$

$I_E \approx I_C \,, I_C \gg I_B$



$$\frac{U_{R2}}{U_b} = \frac{R_2}{R_1 + R_2}$$

$$U_{R2} = 0{,}7\,\mathrm{V} + I_E \cdot R_E \quad (I_E \approx I_C)$$

$$= 0{,}7\,\mathrm{V} + 2\,\mathrm{mA} \cdot 1{,}1\,\mathrm{k\Omega} = 2{,}9\,\mathrm{V}$$

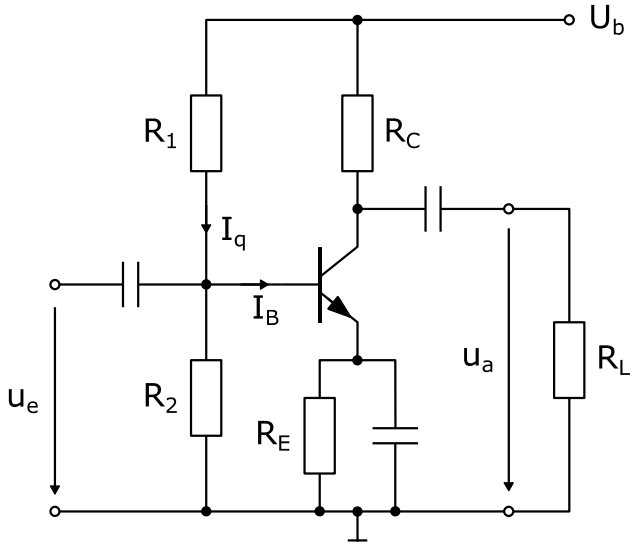
$$(R_1 + R_2) = \frac{R_2}{U_{R2}} \cdot U_b \quad \leftrightarrow \quad R_1 = \frac{R_2}{U_{R2}} U_b - R_2$$

$$= 7{,}51\,\mathrm{k\Omega}$$

$$I_q = \frac{U_{R2}}{R_2} = 1{,}61\,\mathrm{mA}$$

Aufgabe 2

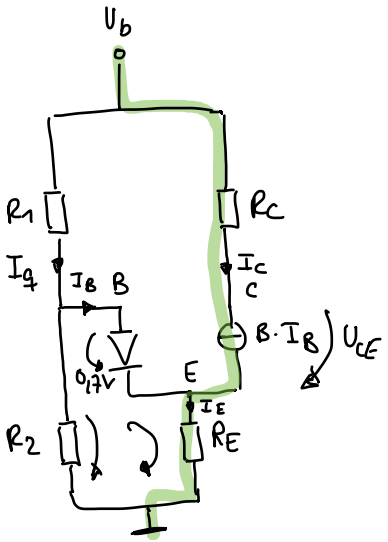
d) ges: R_C



$$U_b = I_C \cdot (R_C + R_E) + U_{CE}$$

$$R_C = \frac{U_b - U_{CE}}{I_C} - R_E$$

$$= 3{,}9\ \text{k}\Omega$$



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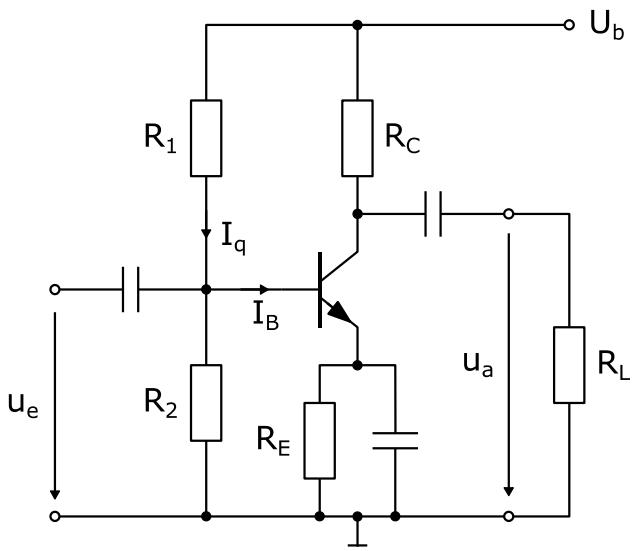
Aufgabe 2

e) ges: I_B, S



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$U_b = 15\ \mathrm{V}$
$U_{BE,on} = 0{,}7\ \mathrm{V}$
$I_C = 2\ \mathrm{mA}$
$U_{CE} = 5\ \mathrm{V}$

$$I_B = \frac{I_C}{B} = \frac{2\,\mathrm{mA}}{290} = 6{,}9\,\mu\mathrm{A}$$

Annahme $I_B << I_q$

$$S = \frac{I_C}{U_T} = \frac{2\,\mathrm{mA}}{26\,\mathrm{mV}} = 76{,}92\,\mathrm{mS}$$

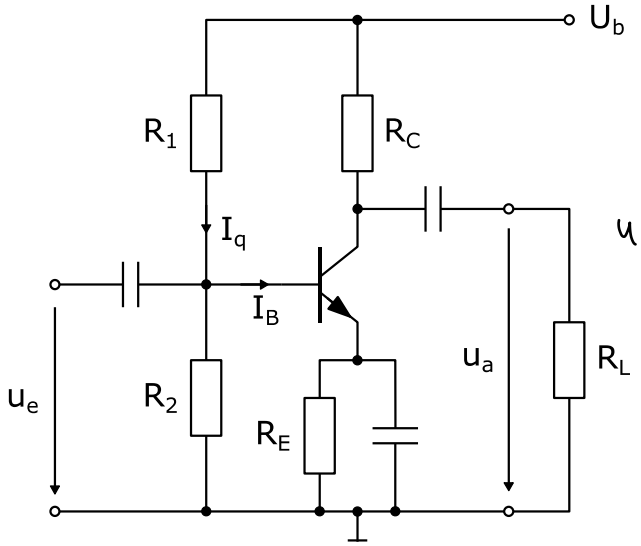
Datenblatt BC 548B

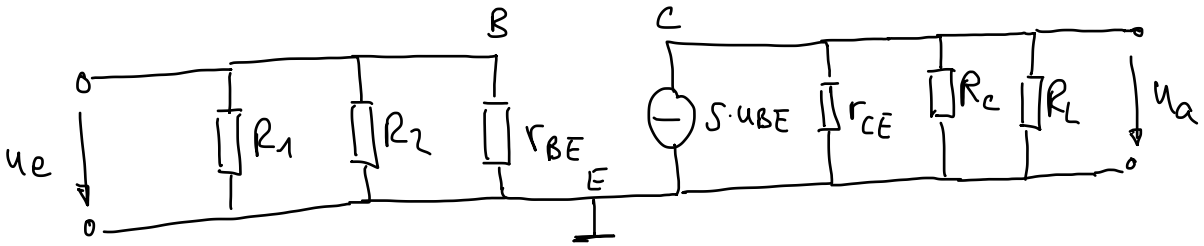
ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted) (Continued)

Characteristic		Symbol	Min	Typ	Max	Unit
ON CHARACTERISTICS						
DC Current Gain		h_{FE}				—
(I_C = 10 µA, V_{CE} = 5.0 V)	BC547A/548A		—	90	—	
	BC546B/547B/548B		—	150	—	
	BC548C		—	270	—	
(I_C = 2.0 mA, V_{CE} = 5.0 V)	BC546		110	—	450	
	BC547		110	—	800	
	BC548		110	—	800	
	BC547A/548A		110	180	220	
	BC546B/547B/548B		200	290	450	
	BC547C/BC548C		420	520	800	
(I_C = 100 mA, V_{CE} = 5.0 V)	BC547A/548A		—	120	—	
	BC546B/547B/548B		—	180	—	
	BC548C		—	300	—	
Collector–Emitter Saturation Voltage		$V_{CE(sat)}$				V
(I_C = 10 mA, I_B = 0.5 mA)			—	0.09	0.25	
(I_C = 100 mA, I_B = 5.0 mA)			—	0.2	0.6	
(I_C = 10 mA, I_B = See Note 1)			—	0.3	0.6	
Base–Emitter Saturation Voltage		$V_{BE(sat)}$	—	0.7	—	V
(I_C = 10 mA, I_B = 0.5 mA)						
Base–Emitter On Voltage		$V_{BE(on)}$				V
(I_C = 2.0 mA, V_{CE} = 5.0 V)			0.55	—	0.7	
(I_C = 10 mA, V_{CE} = 5.0 V)			—	—	0.77	
SMALL–SIGNAL CHARACTERISTICS						
Current–Gain — Bandwidth Product		f_T				MHz
(I_C = 10 mA, V_{CE} = 5.0 V, f = 100 MHz)	BC546		150	300	—	
	BC547		150	300	—	
	BC548		150	300	—	
Output Capacitance		C_{obo}	—	1.7	4.5	pF
(V_{CB} = 10 V, I_C = 0, f = 1.0 MHz)						
Input Capacitance		C_{ibo}	—	10	—	pF
(V_{EB} = 0.5 V, I_C = 0, f = 1.0 MHz)						
Small–Signal Current Gain		h_{fe}				—
(I_C = 2.0 mA, V_{CE} = 5.0 V, f = 1.0 kHz)	BC546		125	—	500	
	BC547/548		125	—	900	
	BC547A/548A		125	220	260	
	BC546B/547B/548B		240	330	500	
	BC547C/548C		450	600	900	

Aufgabe 2

f) ges: Kleinsignalersatzschaltbild

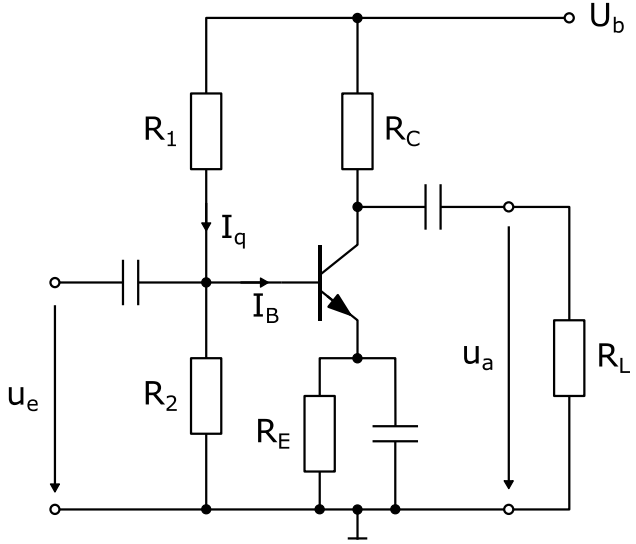




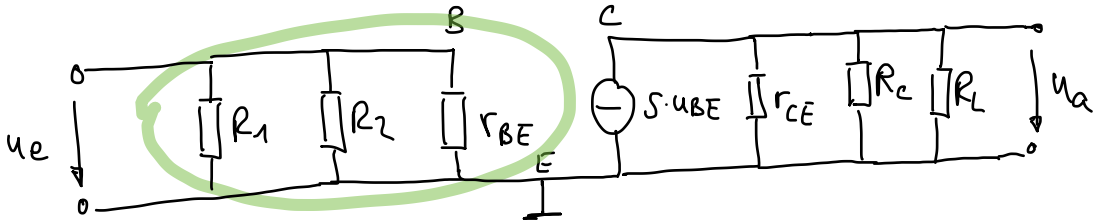
$$R_2 = 1{,}8\ \mathrm{k\Omega}$$
$$R_\mathrm{E} = 1{,}1\ \mathrm{k\Omega}$$
$$U_\mathrm{b} = 15\ \mathrm{V}$$
$$U_\mathrm{BE,on} = 0{,}7\ \mathrm{V}$$
$$I_\mathrm{C} = 2\ \mathrm{mA}$$
$$U_\mathrm{CE} = 5\ \mathrm{V}$$

Aufgabe 2

g) ges: r_e



$R_2 = 1{,}8\ \mathrm{k\Omega}$
$R_E = 1{,}1\ \mathrm{k\Omega}$
$U_b = 15\ \mathrm{V}$
$U_{BE,on} = 0{,}7\ \mathrm{V}$
$I_C = 2\ \mathrm{mA}$
$U_{CE} = 5\ \mathrm{V}$



$r_e = R_1 \,||\, R_2 \,||\, r_{BE}$ (7,51 kΩ, 1,8 kΩ)

$= \frac{\beta}{S} = \frac{330}{76{,}92\ \mathrm{mS}}$

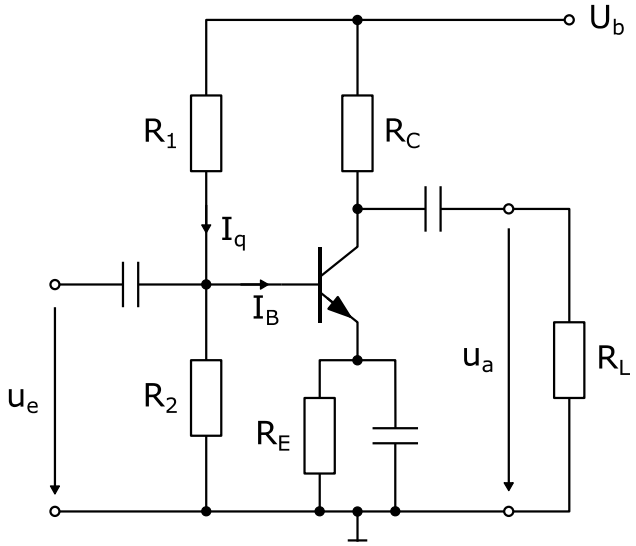
$r_{BE} = 4{,}3\ \mathrm{k\Omega}$

$= \frac{R_1 \cdot R_2}{R_1 + R_2} \,||\, r_{BE} = \frac{R_1 R_2 r_{BE}}{R_1 \cdot R_2 + R_1 \cdot r_{BE} + R_2 \cdot r_{BE}}$

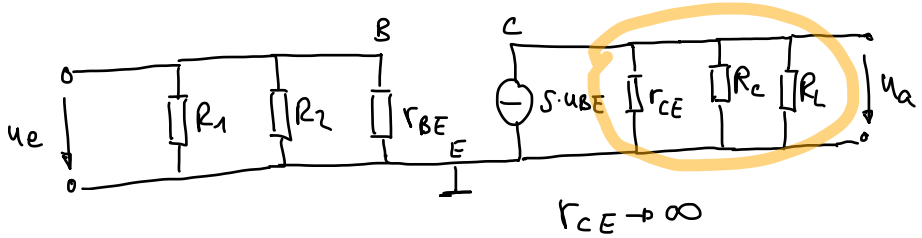
$= 1{,}085\ \mathrm{k\Omega}$ //

Aufgabe 2

h) ges: r_a, A für 1) $R_L = \infty$, 2) $R_L = 3{,}9\ \mathrm{k\Omega}$



$R_2 = 1{,}8\ \mathrm{k\Omega}$
$R_E = 1{,}1\ \mathrm{k\Omega}$
$U_b = 15\ \mathrm{V}$
$U_{BE,on} = 0{,}7\ \mathrm{V}$
$I_C = 2\ \mathrm{mA}$
$U_{CE} = 5\ \mathrm{V}$



$$r_a = R_C \parallel R_L = \frac{R_C R_L}{R_C + R_L}$$

1) $R_L = \infty$ $\quad r_a = R_C = 3{,}9\ \mathrm{k\Omega}$

2) $R_L = 3{,}9\ \mathrm{k\Omega}$ $\quad r_a = 1{,}85\ \mathrm{k\Omega}$

$$A = \frac{u_a}{u_e} = -S \cdot r_a$$

$\hookrightarrow 76{,}92\ \mathrm{mS}$

1) $R_L = \infty \rightarrow A = -300$

2) $R_L = 3{,}9\ \mathrm{k\Omega} \rightarrow A = -150$

Aufgabe 2

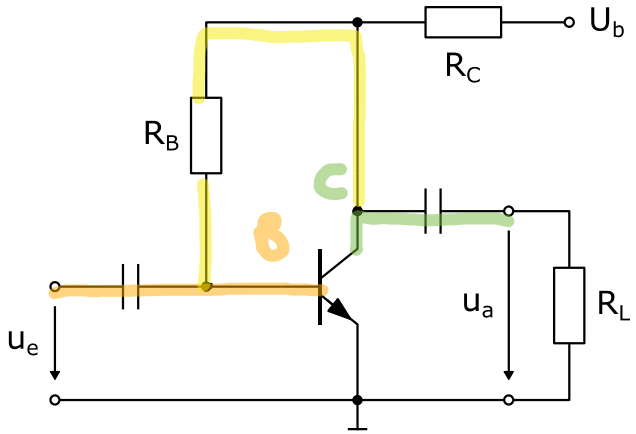
i) ges: Vor- und Nachteile

Vorteil:
- geringere Temperaturabhängigkeit
- A nur noch von Widerständen abhängig

Nachteil:
- A ist geringer

Aufgabe 3

a) ges: Grundschaltung

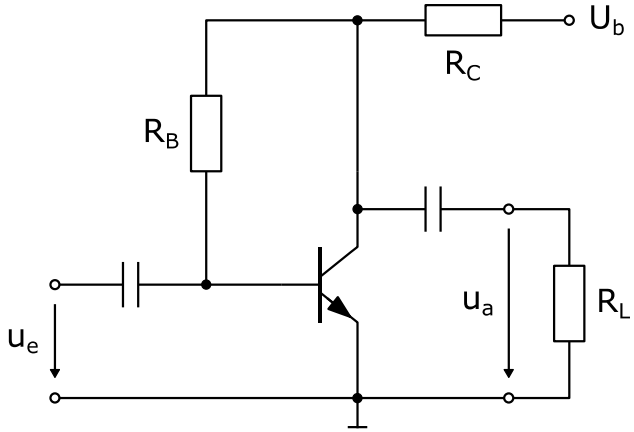


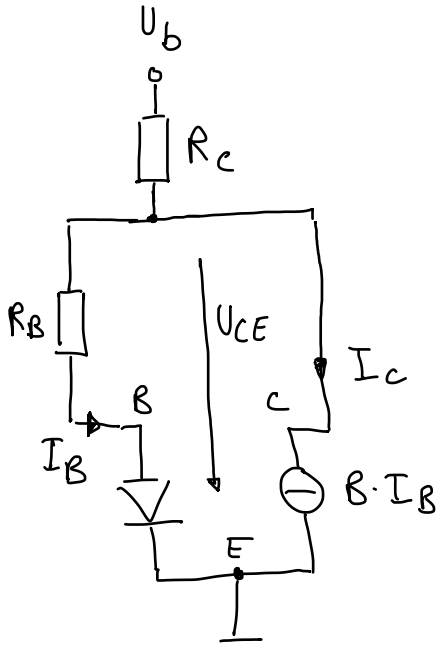
Emitterschaltung mit Spannungsgegenkopplung

$$R_B = 220\ \text{k}\Omega$$
$$R_C = 10\ \text{k}\Omega$$
$$R_L = 4{,}7\ \text{k}\Omega$$
$$U_b = 12\ \text{V}$$
$$B = \beta = 120$$

Aufgabe 3

b) ges: Großsignalersatzschaltbild

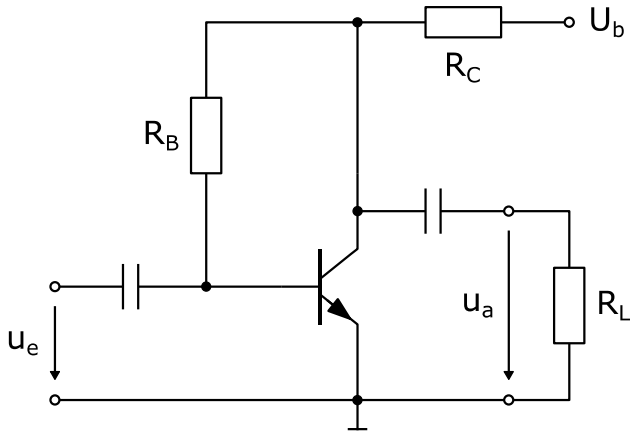




$$R_\mathrm{B} = 220\ \mathrm{k\Omega}$$
$$R_\mathrm{C} = 10\ \mathrm{k\Omega}$$
$$R_\mathrm{L} = 4{,}7\ \mathrm{k\Omega}$$
$$U_\mathrm{b} = 12\ \mathrm{V}$$
$$\mathrm{B} = \beta = 120$$

Aufgabe 3

c) ges: Arbeitspunkt (I_B, I_C, U_{CE})



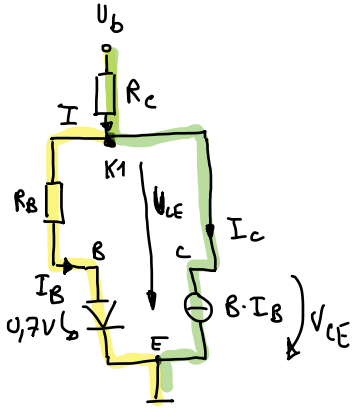
$R_B = 220\ \text{k}\Omega$
$R_C = 10\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 12\ \text{V}$
$B = \beta = 120$

1. Berechnung I_B

$U_b = I \cdot R_C + I_B \cdot R_B + 0{,}7\,V$

$I = I_B + I_C = I_B (1+B)$

$$I_B = \frac{U_b - 0{,}7\,V}{(1+B)R_C + R_B} = 7{,}9\,\mu A$$



2. Berechnung I_C

$I_C = I_B \cdot B = 7{,}9\,\mu A \cdot 120 = 948\,\mu A$

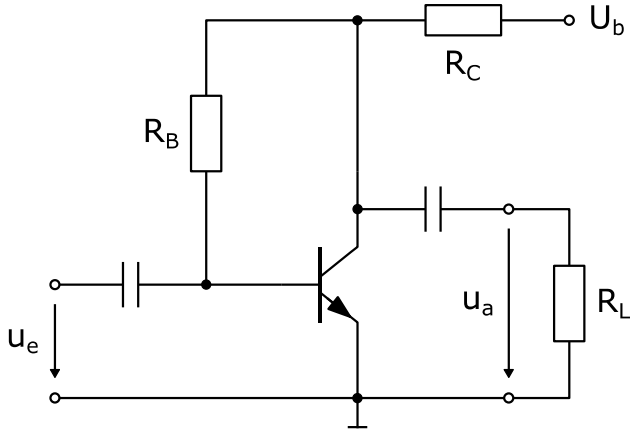
3. Berechnung U_{CE}

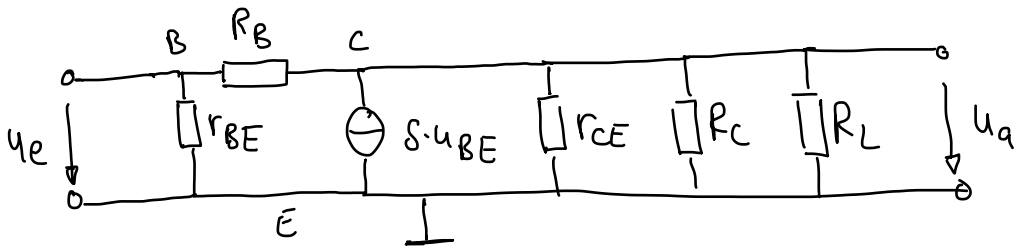
$U_b = I \cdot R_C + U_{CE}$

$U_{CE} = U_b - I_B (1+B) \cdot R_C = 2{,}44\ V$

Aufgabe 3

d) ges: Kleinsignalersatzschaltbild





$R_\mathrm{B} = 220\ \mathrm{k\Omega}$
$R_\mathrm{C} = 10\ \mathrm{k\Omega}$
$R_\mathrm{L} = 4{,}7\ \mathrm{k\Omega}$
$U_\mathrm{b} = 12\ \mathrm{V}$
$\mathrm{B} = \beta = 120$

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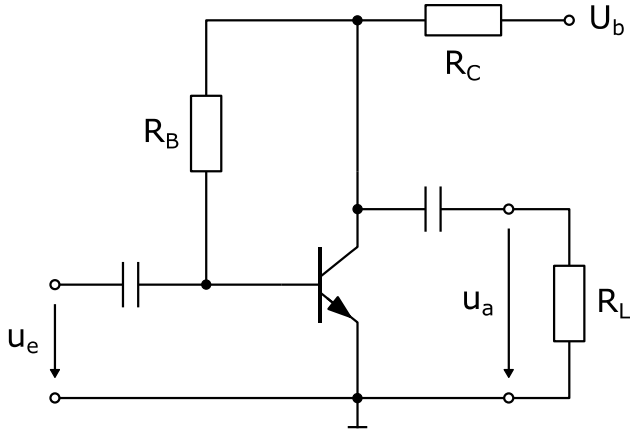
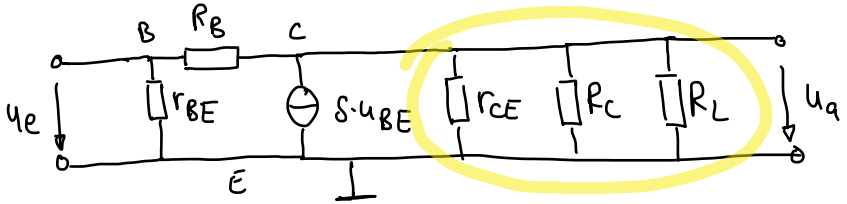
Aufgabe 3

e) $A = \frac{u_a}{u_e}$



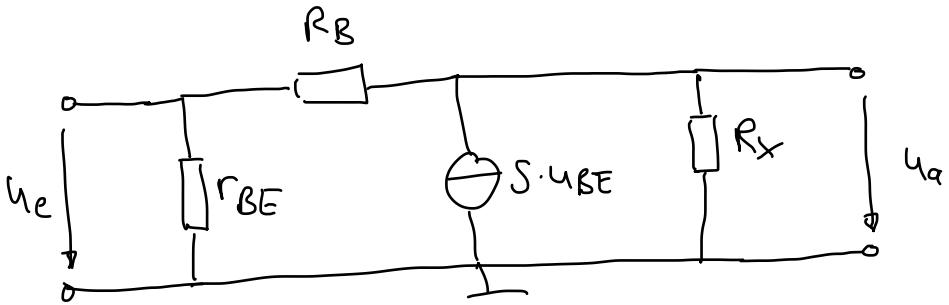
$R_B = 220\ \text{k}\Omega$
$R_C = 10\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 12\ \text{V}$
$B = \beta = 120$



1. $r_{BE} = \frac{\beta}{S}$ mit $S = \frac{I_C}{U_T} = 36{,}46\ \text{mS}$

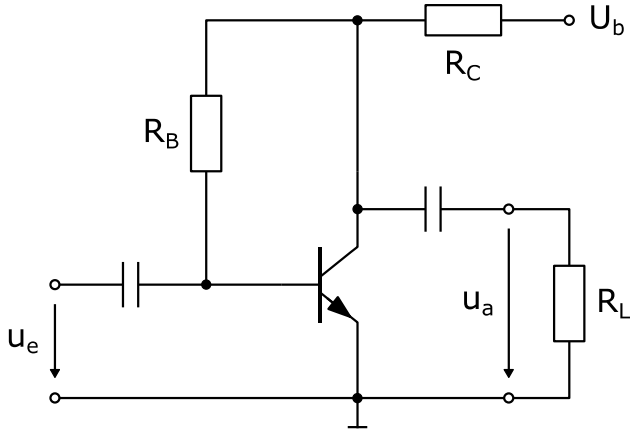
$= 3{,}29\ \text{k}\Omega$

$R_X = r_{CE} \| R_C \| R_L = \frac{R_C R_L}{R_C + R_L} = 3{,}2\ \text{k}\Omega$

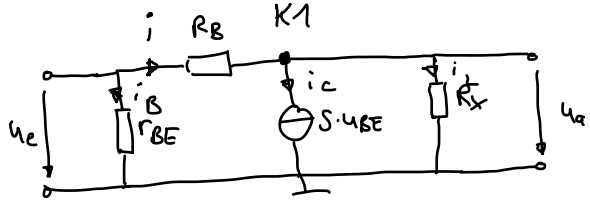


Aufgabe 3

e) $A = \frac{u_a}{u_e}$



$R_B = 220\ \text{k}\Omega$
$R_C = 10\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 12\ \text{V}$
$B = \beta = 120$



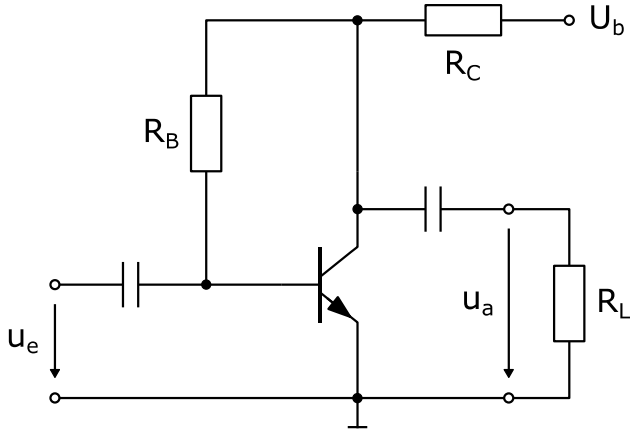
2. geg: $r_{BE}, S, R_B, R_X, \beta$

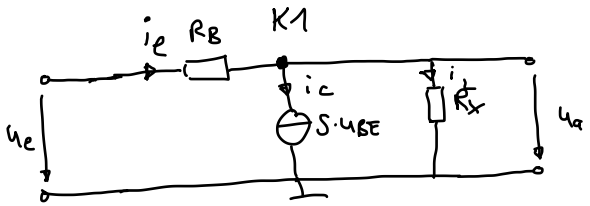
3. $u_e = u_{BE} = i_B \cdot r_{BE}$ (1)
$u_e = i \cdot R_B + u_a$ (2)
$u_{BE} = i R_B + u_{CE}$ (3)
$u_a = i_L \cdot R_X$ (4)
K1: $i = i_C + i_L$ (5)
$i_C = \beta \cdot i_B$ (6)

$$u_e = i R_B + u_a$$
$$= (i_C + i_L) R_B + u_a$$
$$= \left(\beta \cdot i_B + \frac{u_a}{R_X}\right) R_B + u_a$$
$$= \left(\beta \cdot \frac{u_e}{r_{BE}} + \frac{u_a}{R_X}\right) R_B + u_a$$
$$u_e \left(1 - \beta \cdot \frac{1}{r_{BE}} R_B\right) = u_a \left(1 + \frac{R_B}{R_X}\right)$$
$$A = \frac{u_a}{u_e} = \frac{1 - \beta \cdot \frac{R_B}{r_{BE}}}{1 + \frac{R_B}{R_X}} = -115$$

Aufgabe 3

f) r_e





$$r_e = \frac{u_e}{i_e} = \frac{u_e}{\frac{u_e - u_a}{R_B}} = \frac{R_B}{1 - \frac{u_a}{u_e}} = \frac{R_B}{1 - A}$$

$$= 1{,}9\ \text{k}\Omega$$

$R_B = 220\ \text{k}\Omega$
$R_C = 10\ \text{k}\Omega$
$R_L = 4{,}7\ \text{k}\Omega$
$U_b = 12\ \text{V}$
$B = \beta = 120$

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Aufgabe 3

g) Vor- und Nachteile

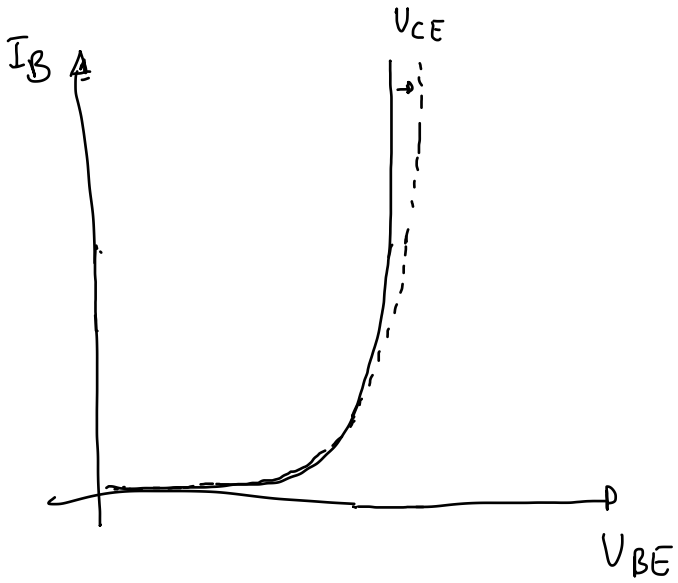
Vorteil: sehr gut kontrollierbarer Klemsignal eingangswiderstand

Nachteil: A ist geringer

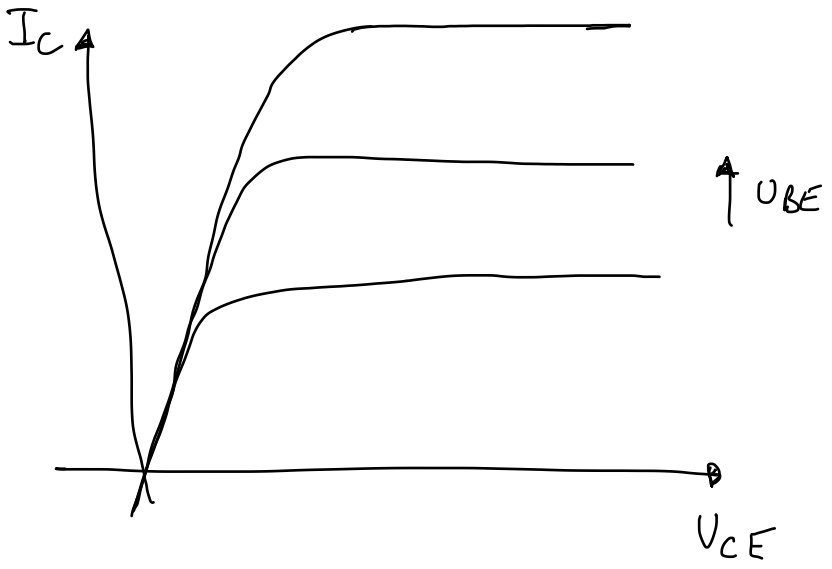
Aufgabe 4

a) ges: Ein- und Ausgangskennlinienfeld eines Bipolartransistors

Eingangskennlinienfeld



Ausgangskennlinienfeld



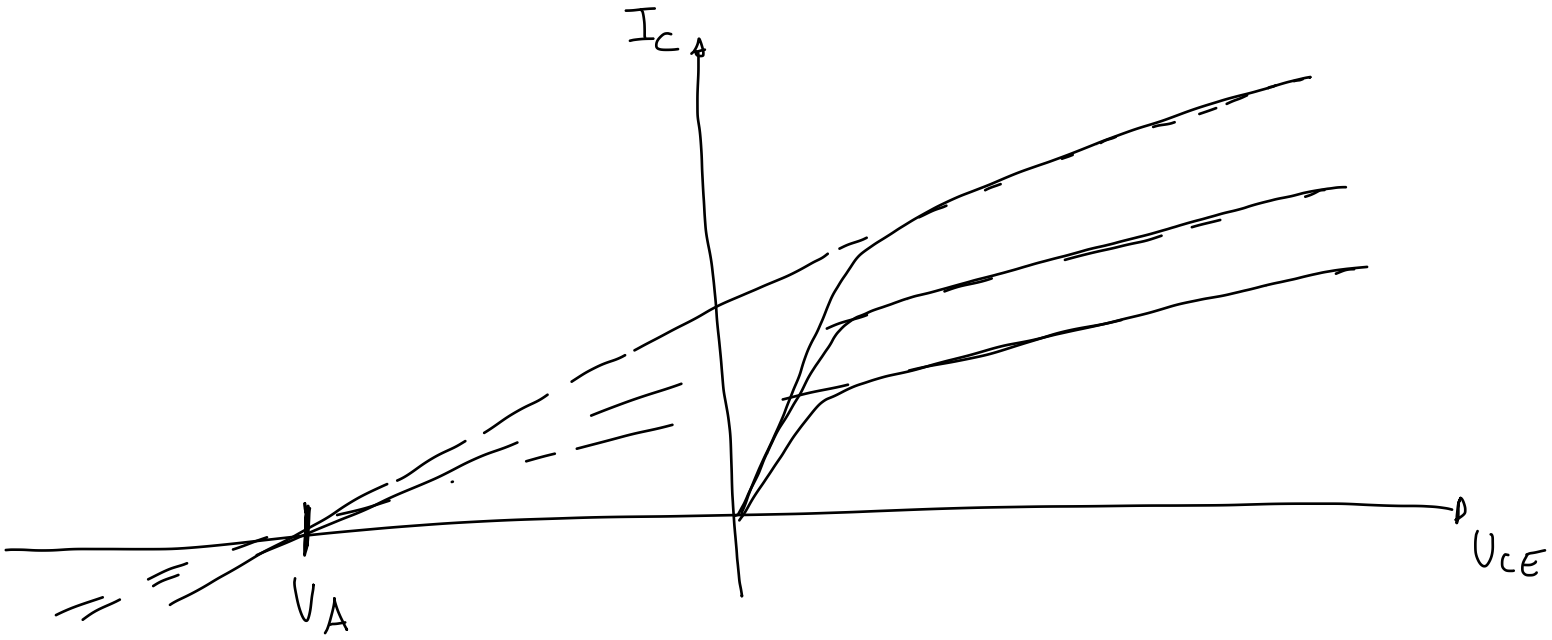
Aufgabe 4

b) ges: Eigenschaften eines guten Bipolartransistors

- r_{CE} sehr groß
- Basis sehr klein

Aufgabe 4

c) ges: Early Effekt



- I_C ist abhängig von U_{CE}
- r_{CE} ist nicht unendlich groß