平成26年度前期東京工業大学学部講義

電子デバイス

Electron Devices

資料（５）　*handout*

Revised

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Green ICE Tokyo Tech Information Communication Energy
Semiconductor Solution Research

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Today's purpose

- Understanding of current-voltage characteristics of common-base, emitter, and collector.
- Understanding of small signal equivalent circuit.

I-V characteristics 電流電圧特性

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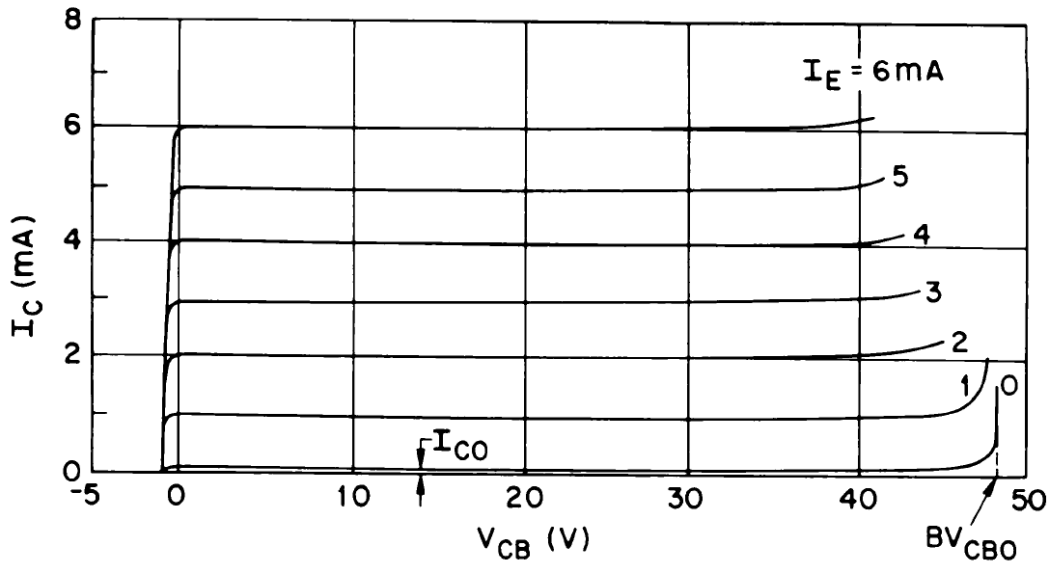
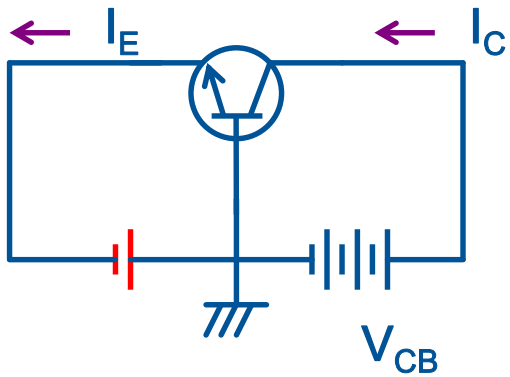
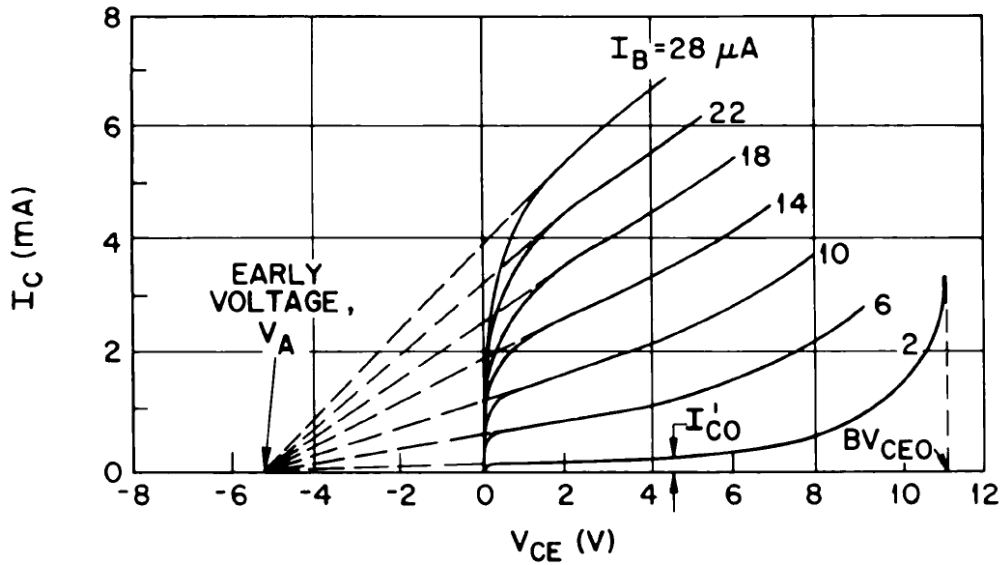
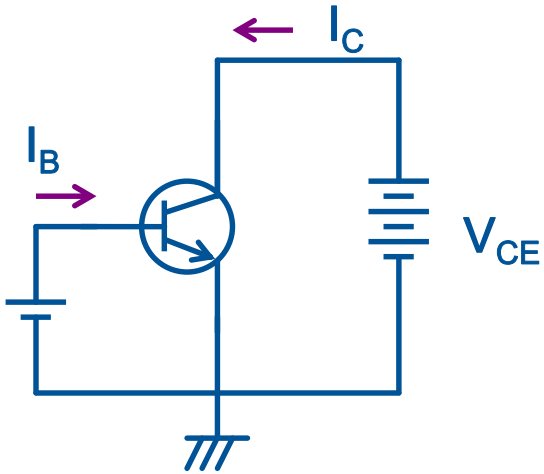
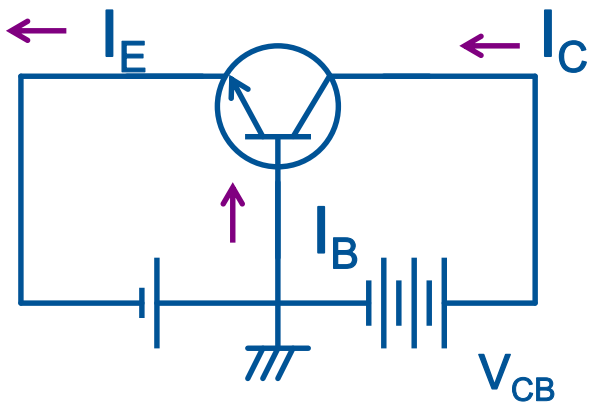


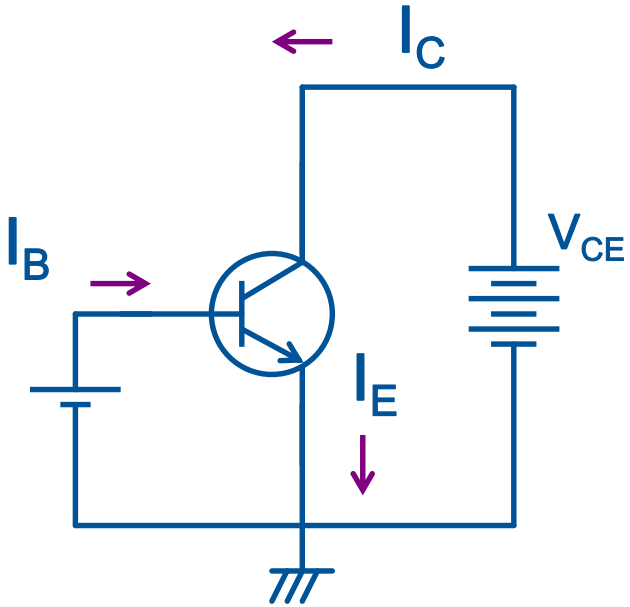






Common emitter エミッタ接地回路





Common base ベース接地回路

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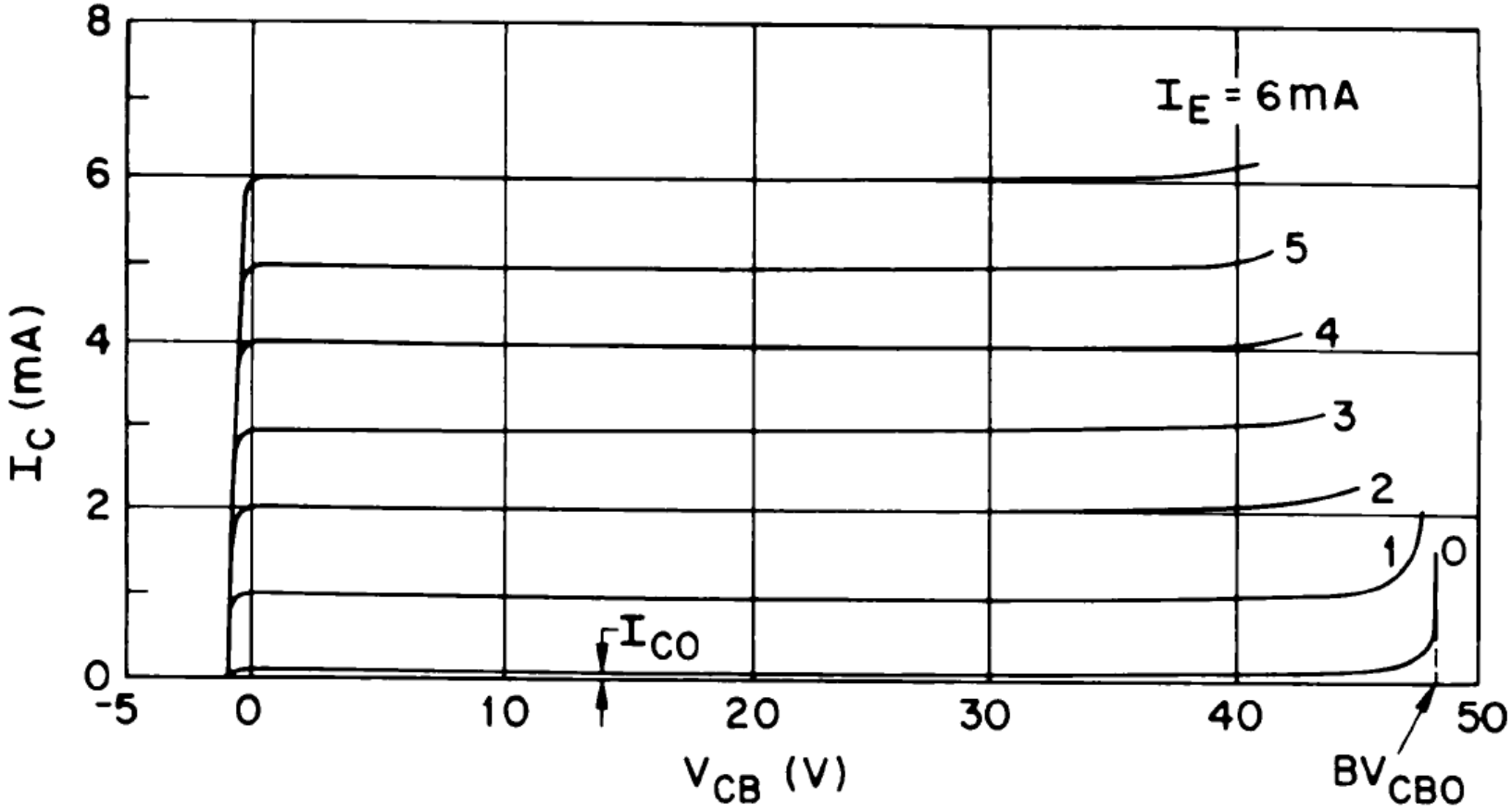
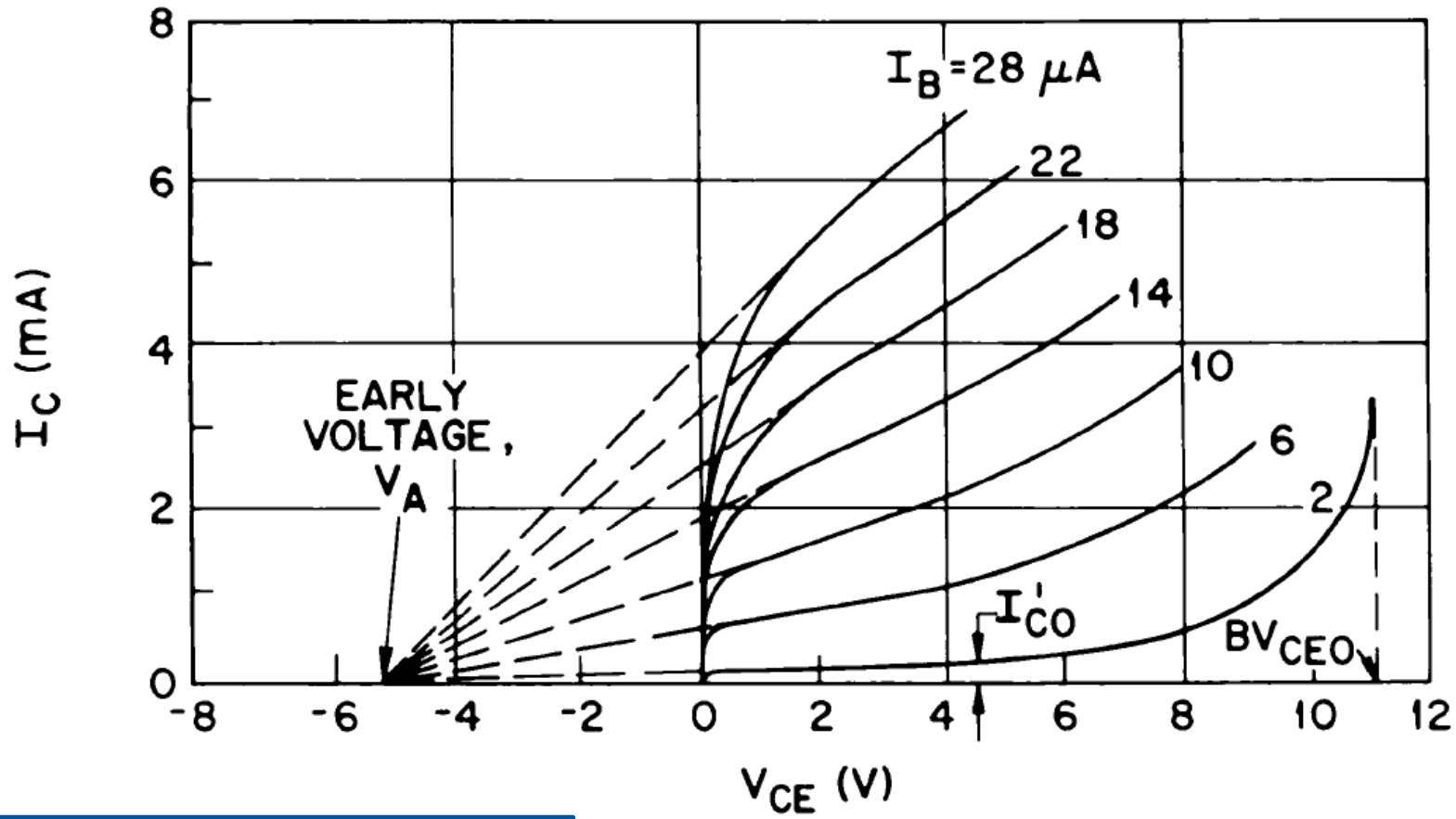
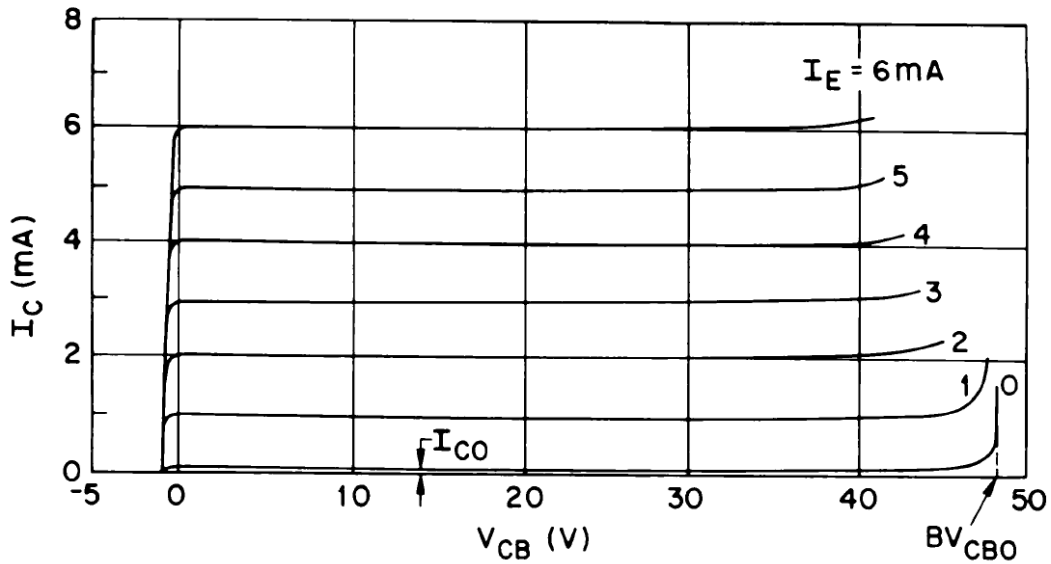
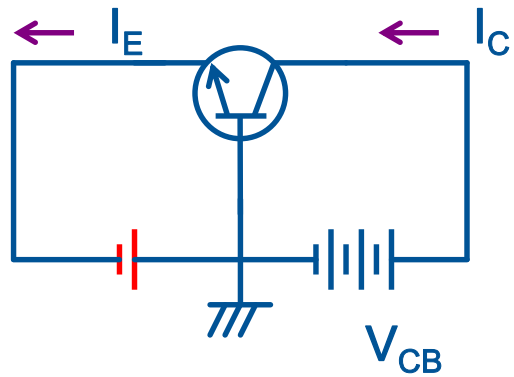


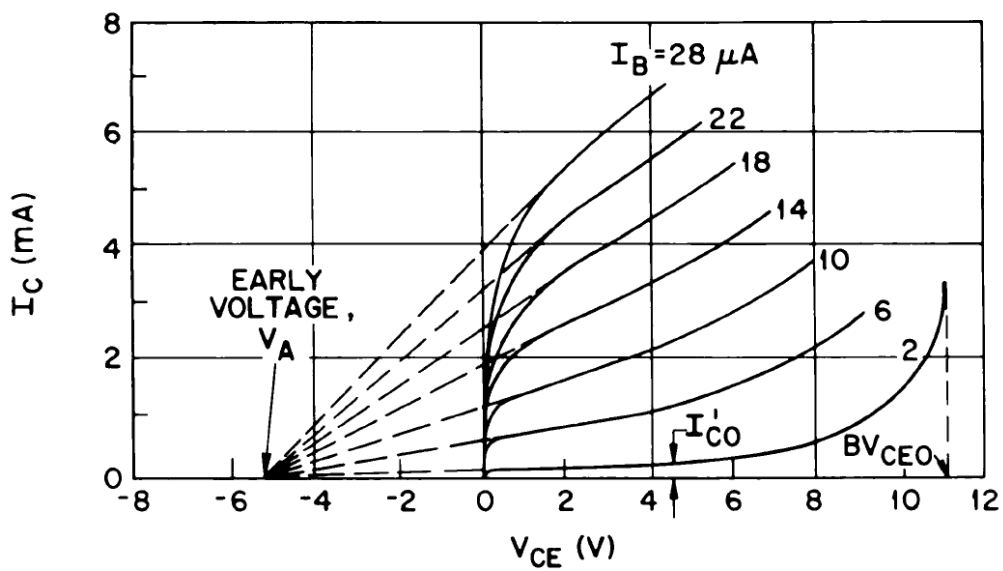
Common emiter エミッタ接地回路

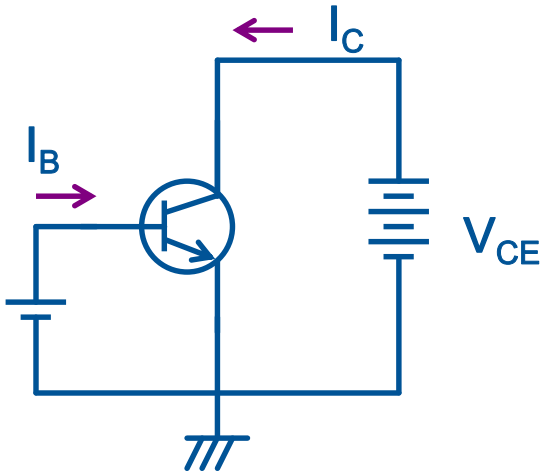


Supplement : I-V characteristics









$$V_A = \frac{qN_{base}{W_B}^2}{\varepsilon_{Si}\varepsilon_o},$$

W_B: *base width*

Supplement： Early effect

- エミッタ接地回路において、VCEを増加させると、ICが増加する。
  - これは、V_{CE}を増加させると、ベース･コレクタ間空乏層が増加することから説明される。
  - コレクタ側空乏層の方が広いが、ベース側空乏層も減少する。実質的にベース幅W_Bが減少するので、
  - $J_E \approx J_C = q\frac{D_B}{W_B}n_{B0}e^{\frac{qV_{BE}}{kT}}$ よりコレクタ電流が増加すると説明される。
- ベース接地回路においても、VCBを増加させると、ベース･コレクタ空乏層が拡がり、上記と同様ベース幅が狭くなり、コレクタ電流がVCBの増加とともに増加すると考えられる。しかし、ベース接地回路において、コレクタ電流はほとんど一定である。何故か？

Supplement : Early effect (1)

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- In common emitter circuit, collector current I_c increases as V_{CE} increase.
- This increase is explained as follows :
  - The collector-base depletion layer width increases with increase of V_{CE}.
  - Although the depletion layer width in collector region is larger than that of base region, the depletion width region is reduced with increase with increase of V_{CE}. Hence, Base width WB reduces with increase of V_{CE}.
  - Then, the collector current increases as $J_E \approx$

$$J_C = q\frac{D_B}{W_B}n_{B0}e^{\frac{qV_{BE}}{kT}}$$

Supplement : Early effect (2)

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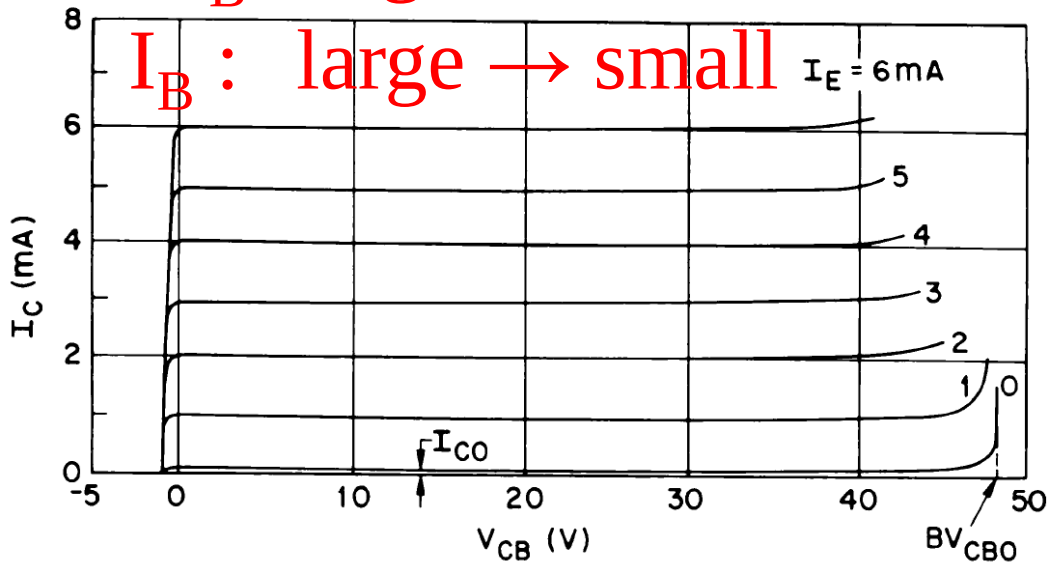
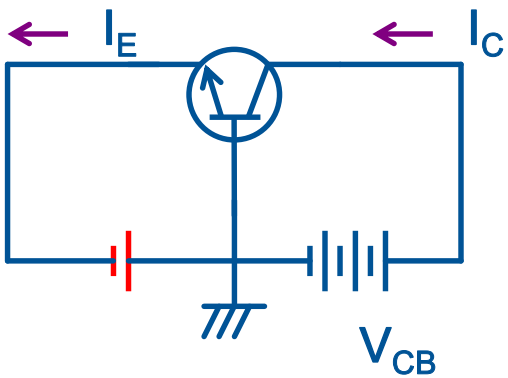
- In common base circuit,
  1. Increase of V_{CB} causes the increase of base-collector depletion layer width.
  2. Then, the W_B reduces.
  3. The reduction of W_B seems to increase the increase of collector current I_C.
- However, in common base circuit, the collector current is independent of V_{CB}. Why the collector current does not increase with V_{CB}?
- In the I_c-V_{CB} characteristic of common-base circuit, the parameter is I_E not I_B. The base width decreases with increase of V_{CB}. On the other hand, to keep the I_E constant, the base current decreases with increase of V_{CB}.

Supplement : Early effect (3)

W_B: large → small

I_B : large → small





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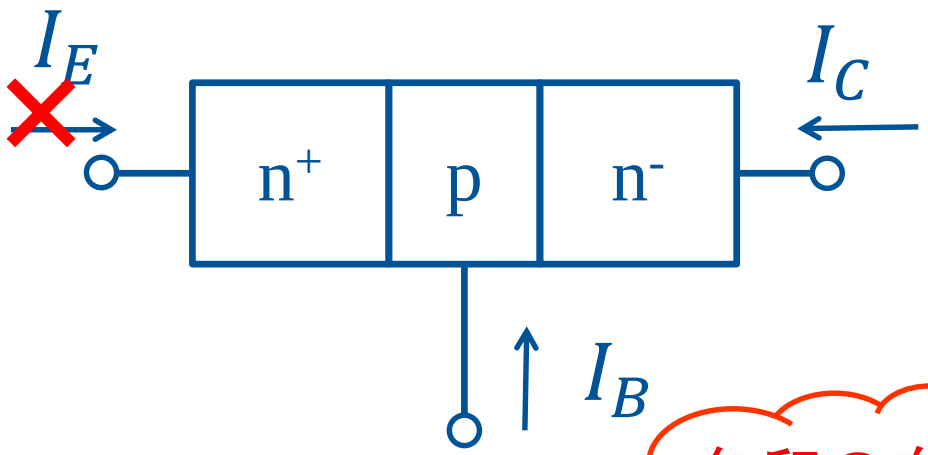
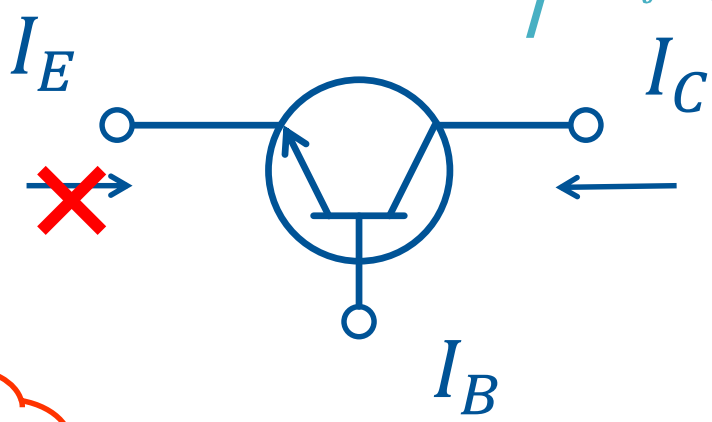
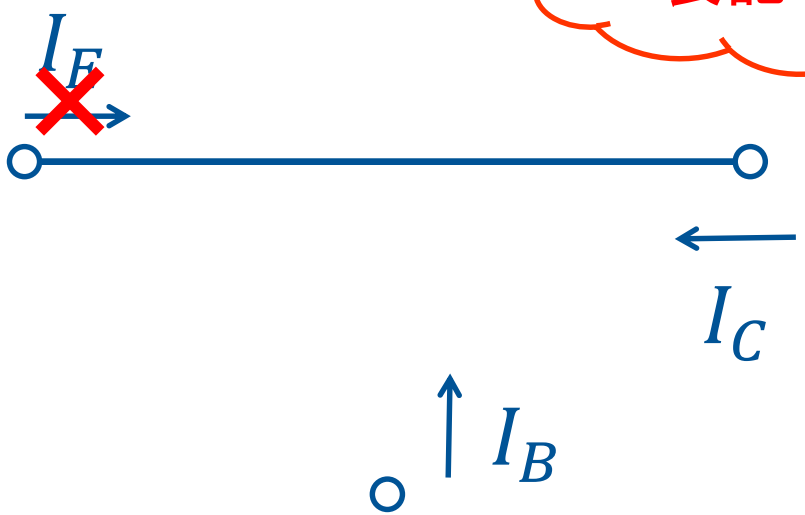
Equivalent circuit 等価回路

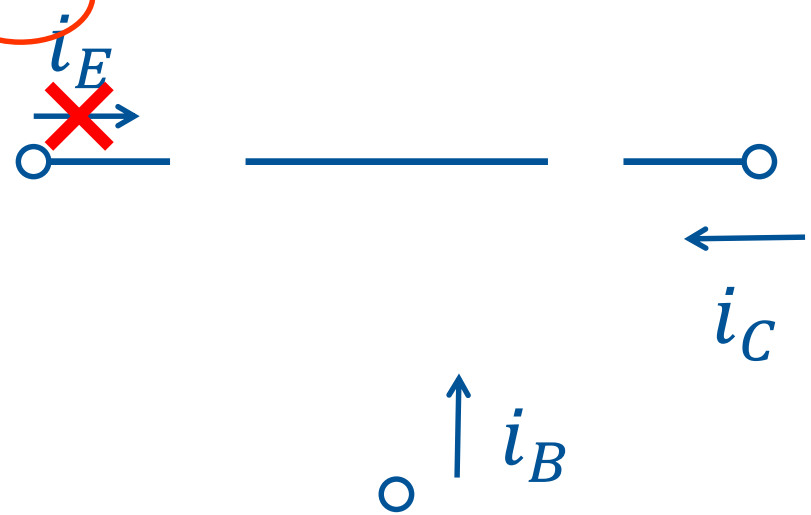
Handout





矢印の向き
表記ミス





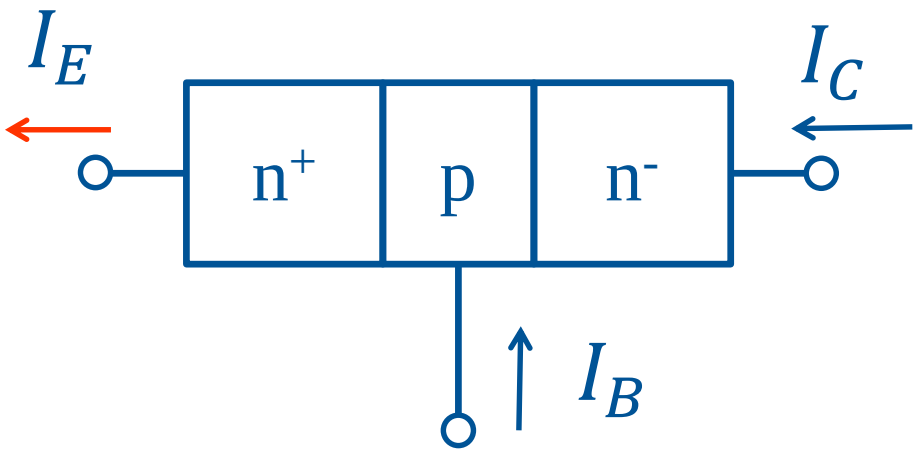
DC equivalent circuit
直流等価回路

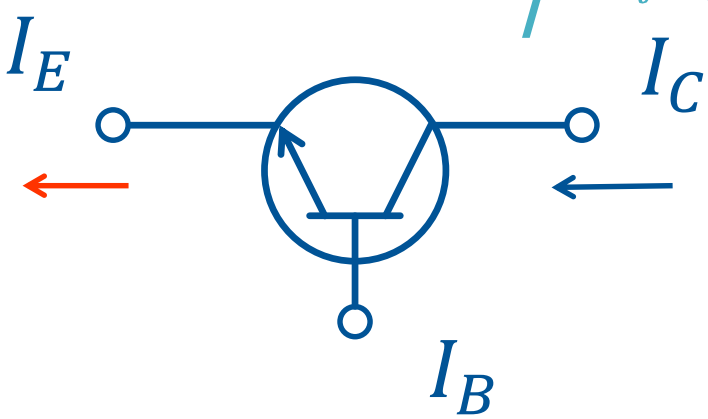
Small signal equivalent circuit at low frequency
小信号等価回路（低周波）

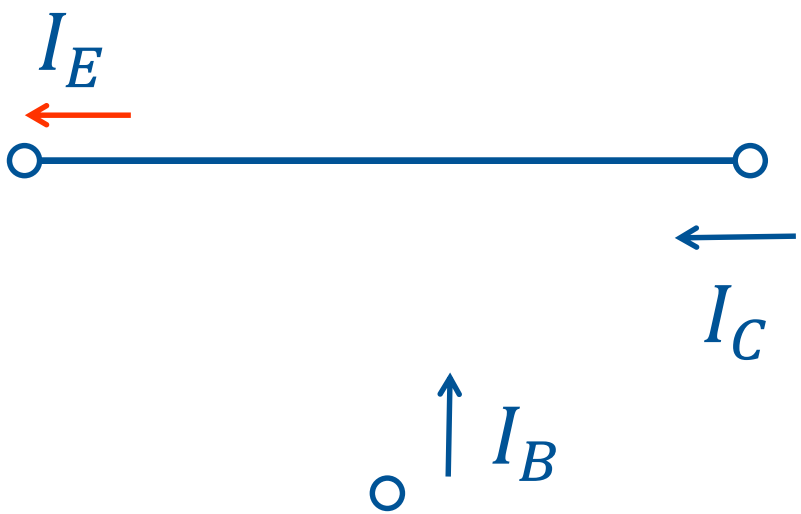
Kazuya Masu

Equivalent circuit 等価回路

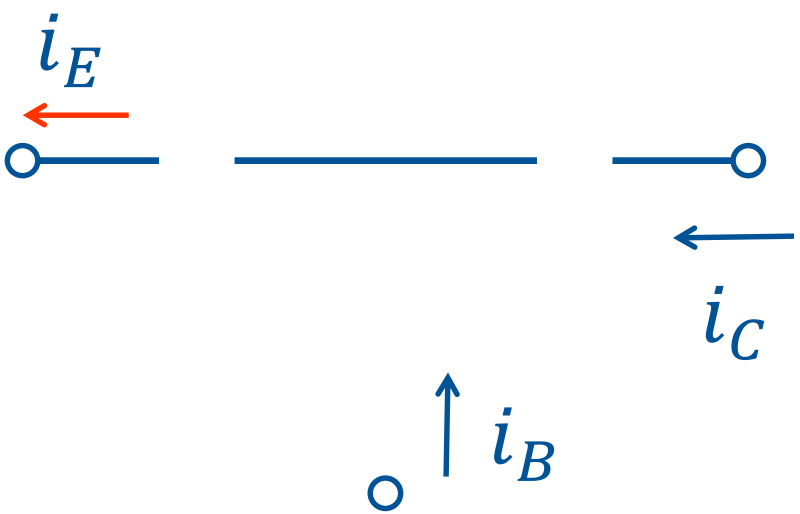
Handout revised







DC equivalent circuit
直流等価回路



Small signal equivalent circuit at low frequency
小信号等価回路（低周波）

Small signal equivalent circuit 等価回路(小信号)

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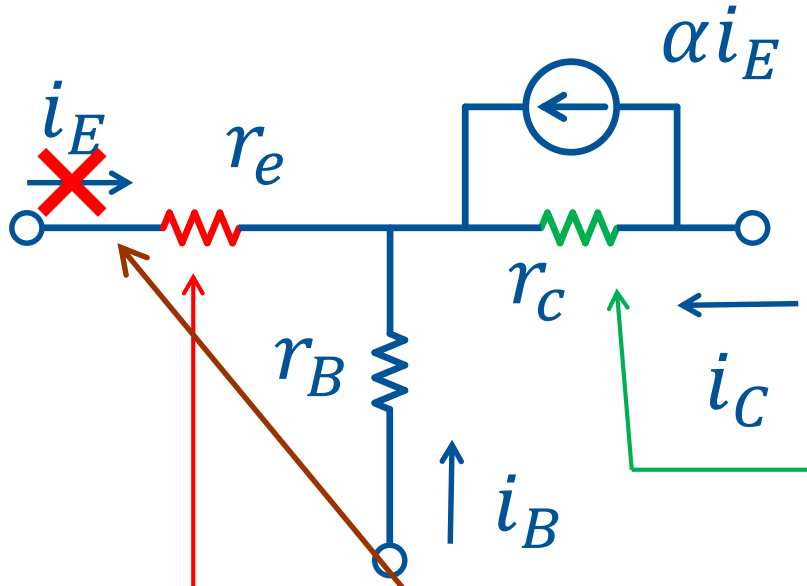
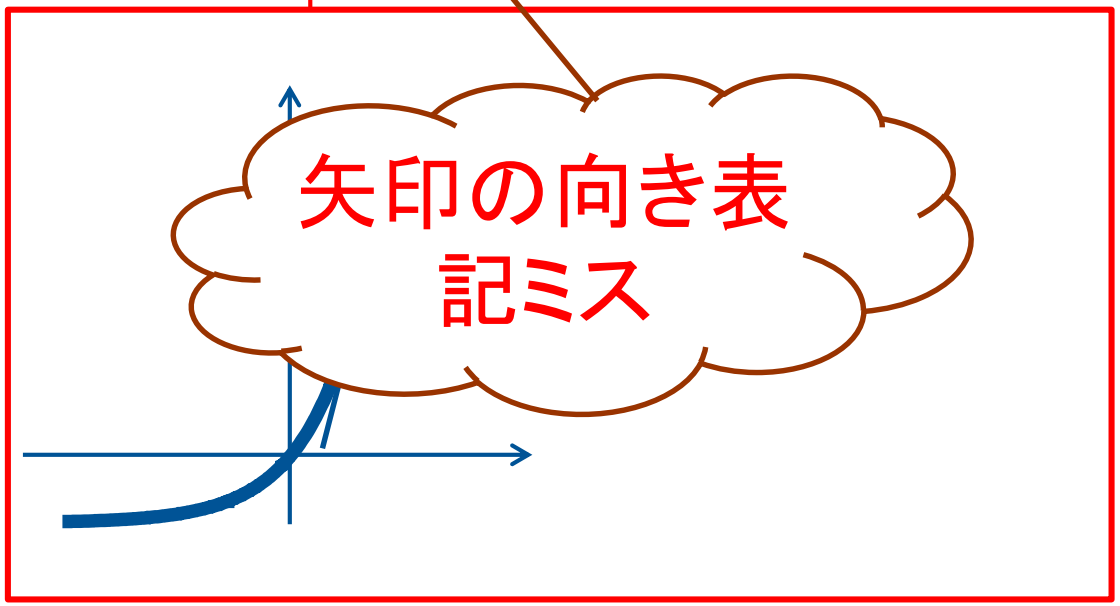
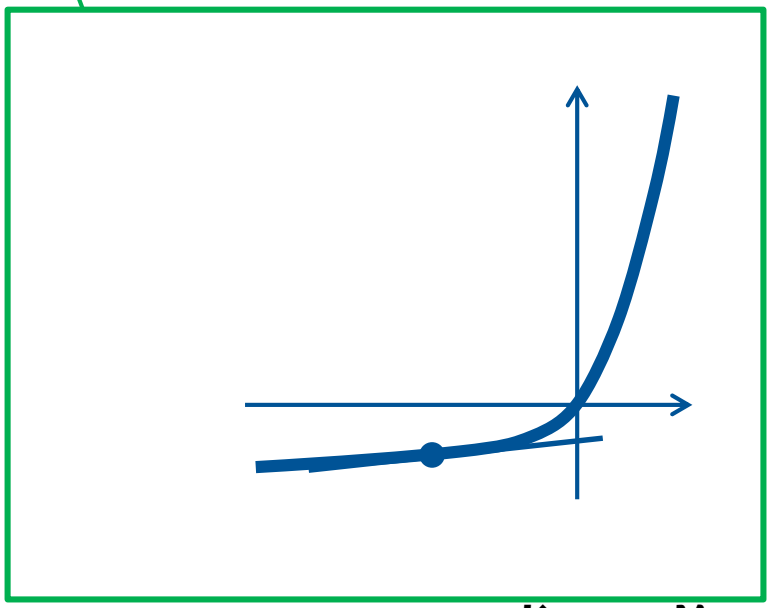
Handout



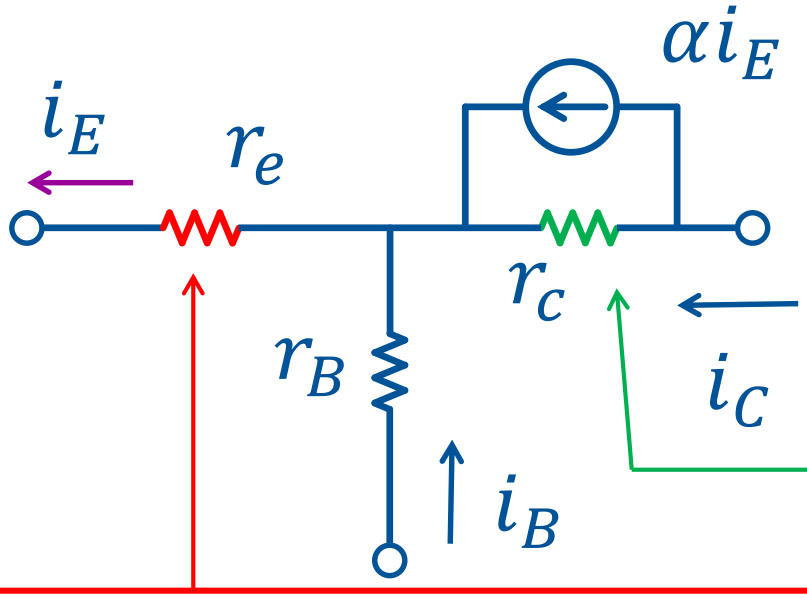
- 小文字は小信号成分を表す。
- 一定条件の直流バイス印加時に小振幅信号を重畳させたときの等価回路





Small signal equivalent circuit 等価回路(小信号)

Revised handout



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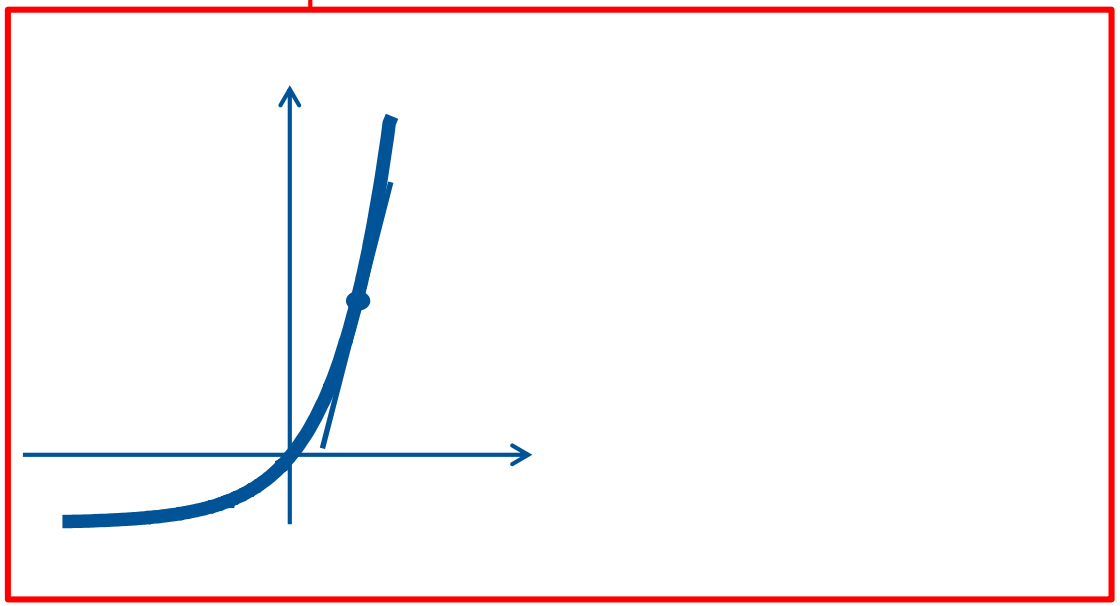
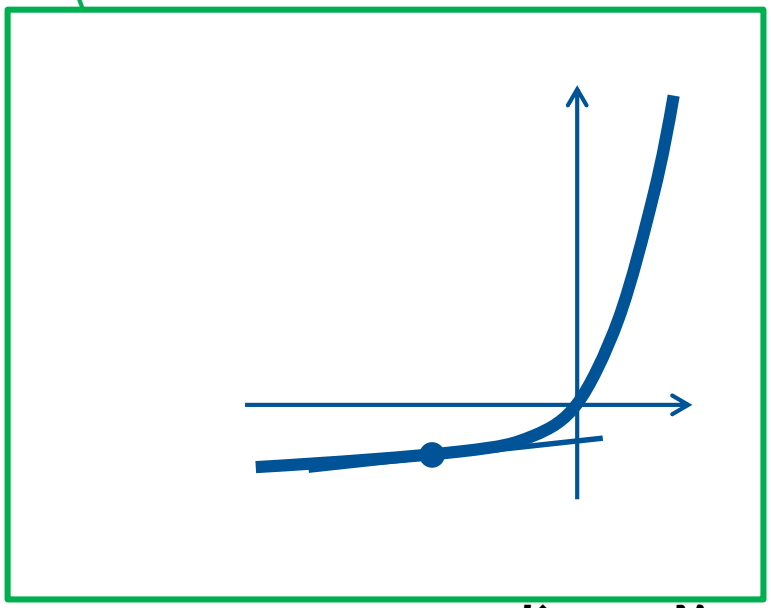
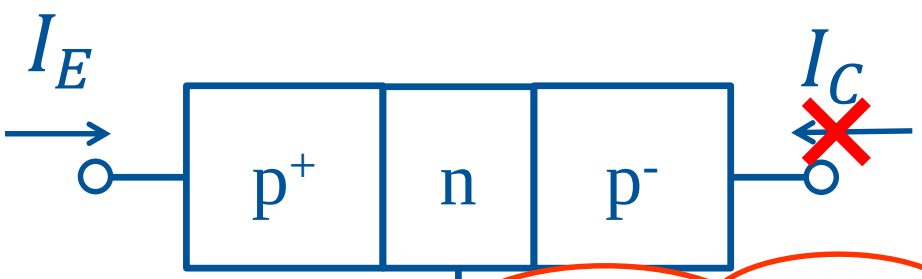
- 一定条件の直流バイス印加時に小振幅信号を重畳させたときの等価回路

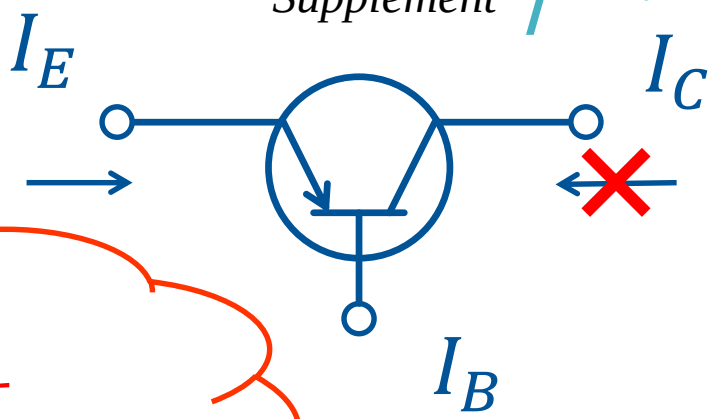




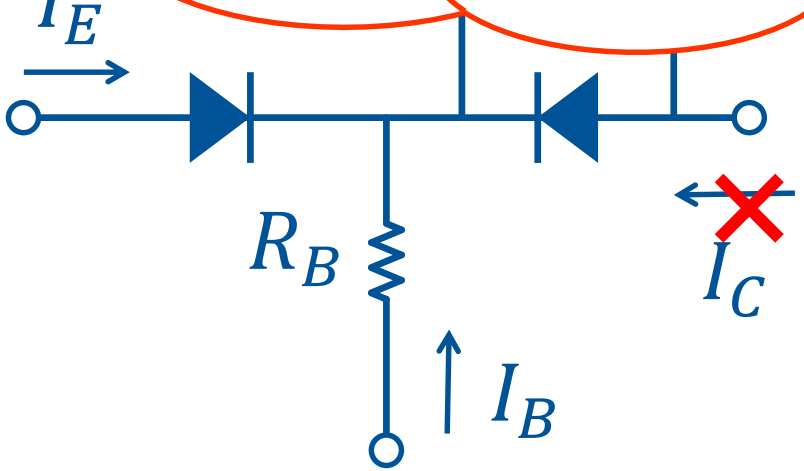
Equivalent circuit for pnp Tr.等価回路 （pnp形）



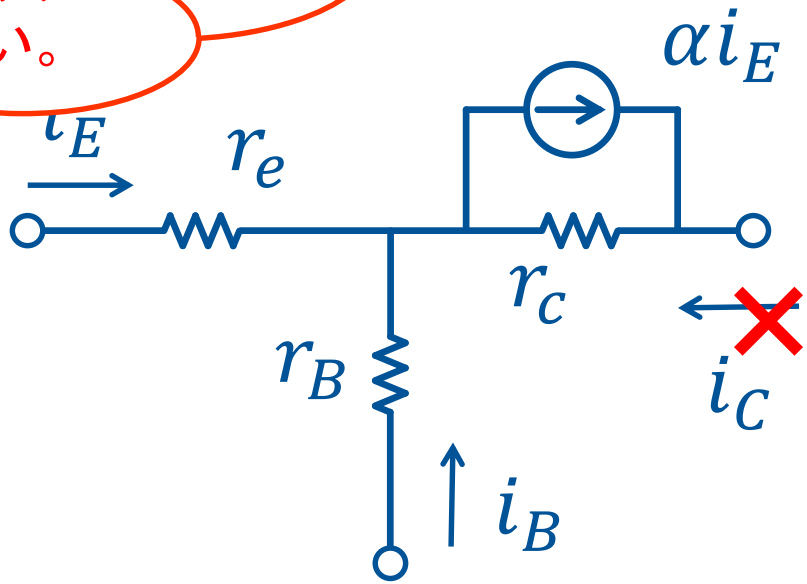
Supplement



電流方向はどちらにとっても良いが、物理的なイメージに近いように表記する場合は、pnp Trの場合は、コレクタ電流は出る方向にとった方が良い。

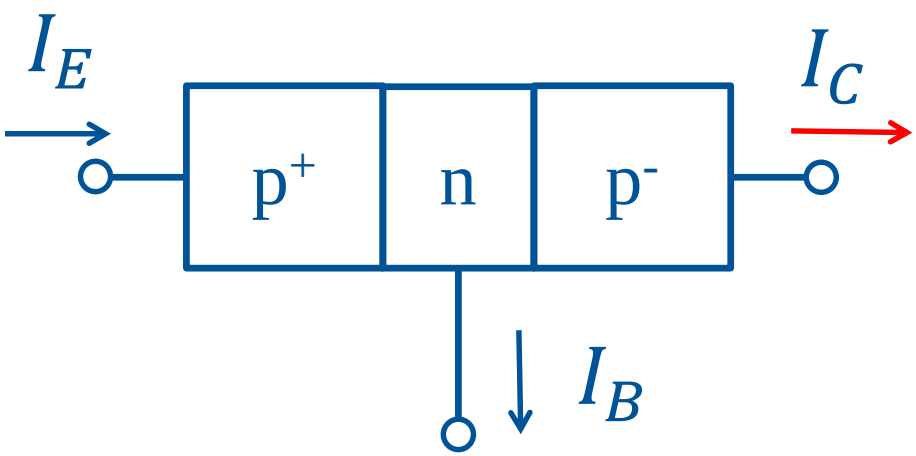


直流等価回路

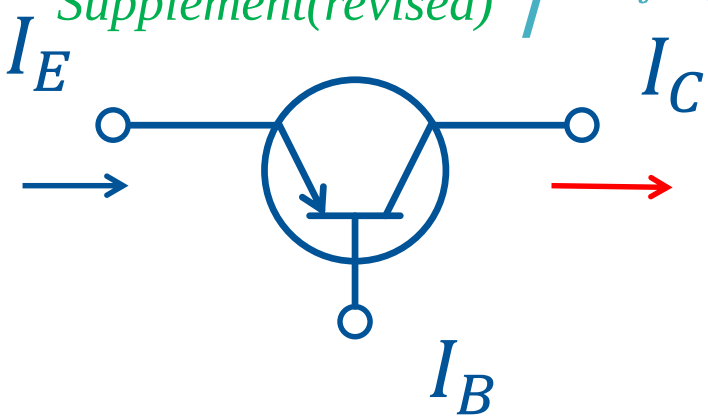


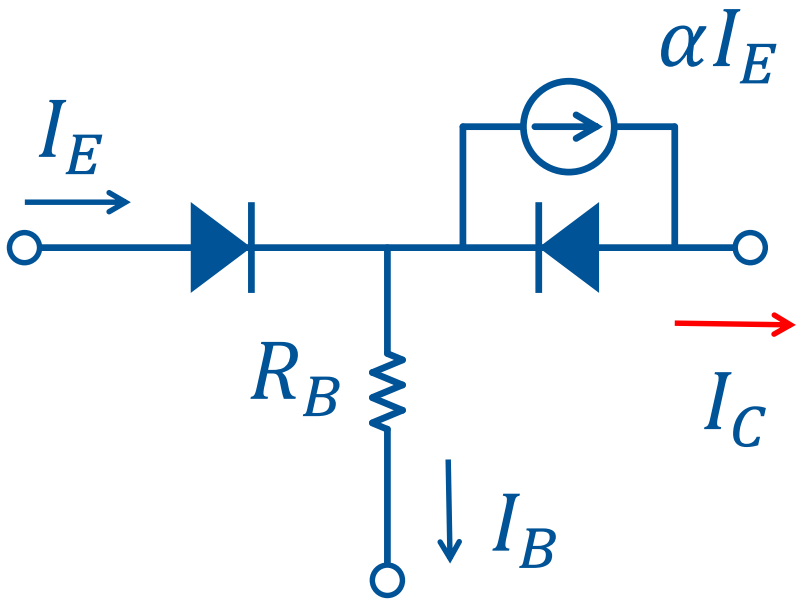
小信号等価回路(低周波)

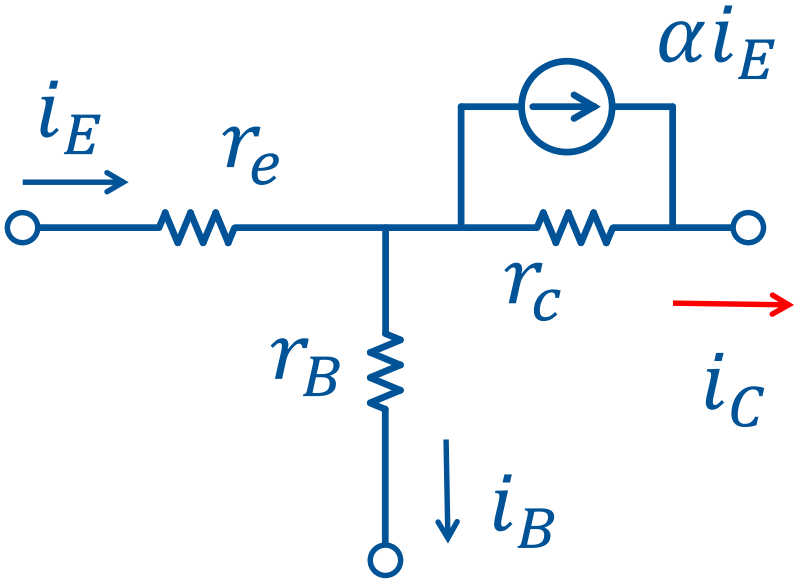
Equivalent circuit for pnp Tr.等価回路 （pnp形）



Supplement(revised)







直流等価回路

小信号等価回路(低周波)

Supplement: current direction

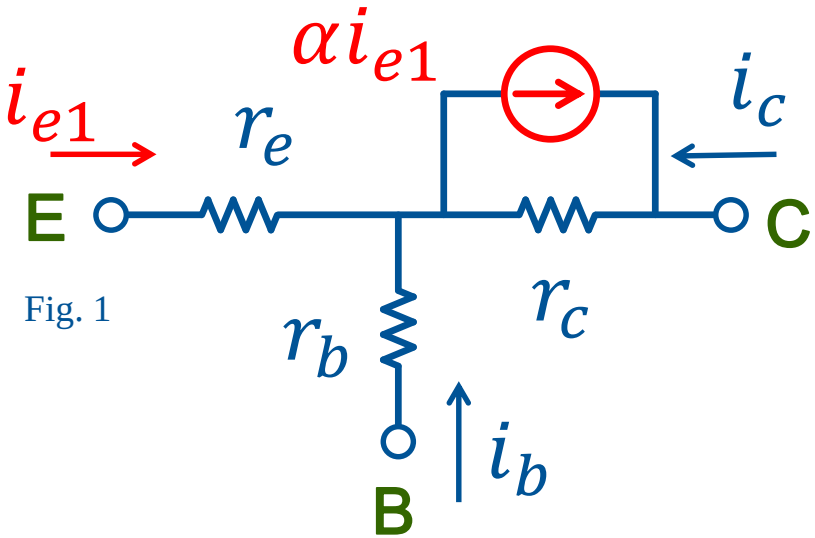


Fig. 1

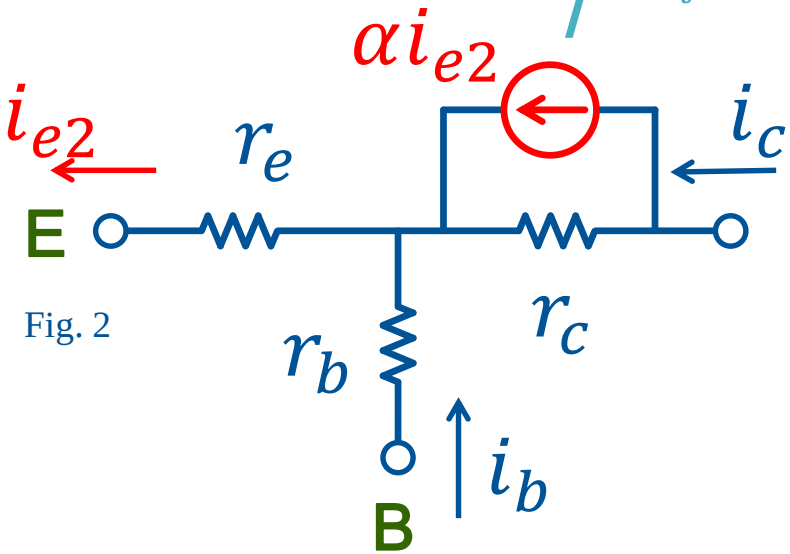


Fig. 2

When drawing the T-type equivalent circuit, the direction of the dependent current source is dependent on the emitter current. As shown in Figs. 1-3, Remind the direction and sign of the current source. The base and collector current directions are freely defined. The relation between the current direction of emitter and current source for npn and pnp tr is the same.
T型等価回路において、電流源の向きはエミッタ電流の方向に依存する。Fig.1～3でそれらの関係を確認すること。どの表記を用いても良い。ベース、コレクタ電流方向は任意である。エミッタ電流方向と電流源の方向の関係は、npnトランジスタ、pnpトランジスタともに同じである。

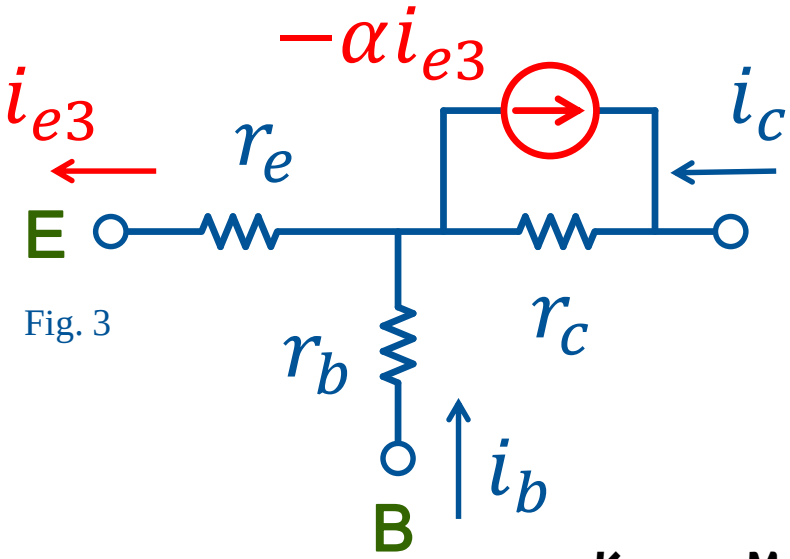
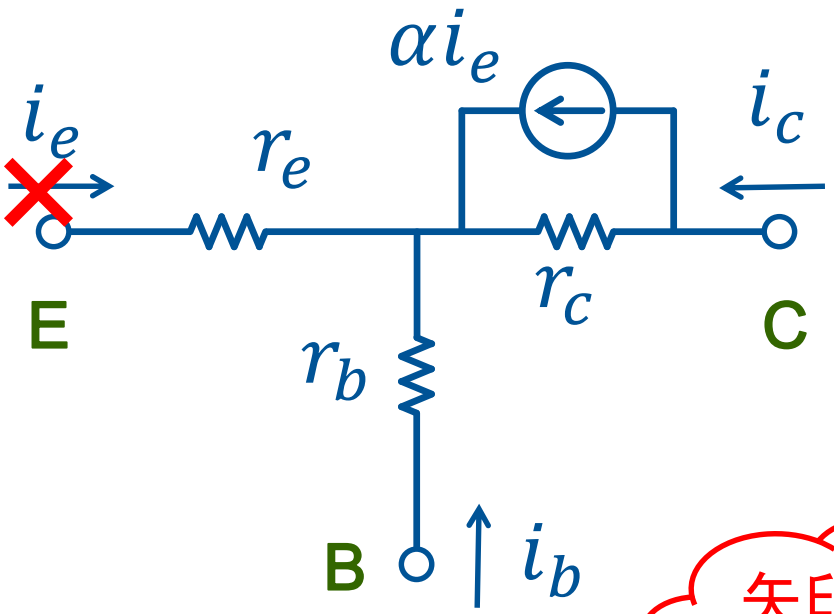
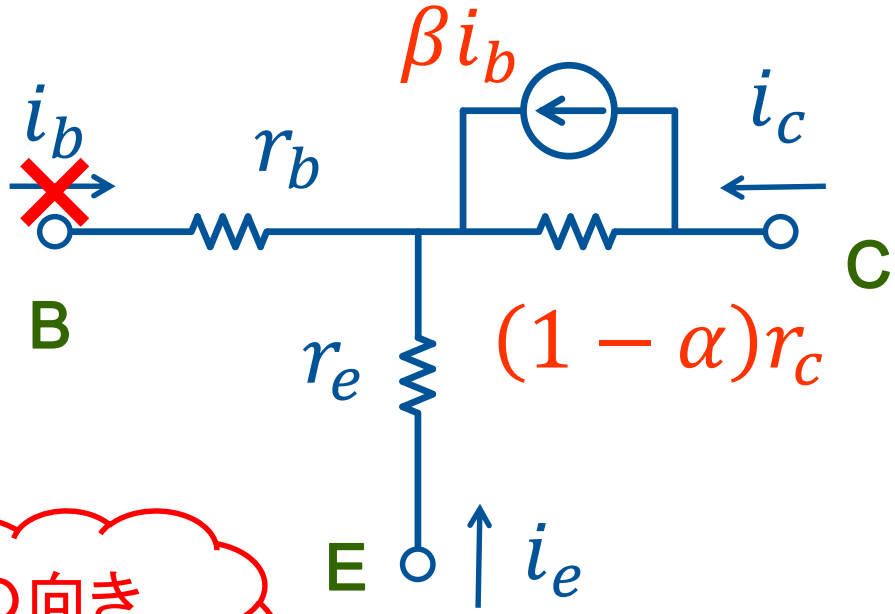


Fig. 3

等価回路(ベース接地・エミッタ接地)



ベース接地

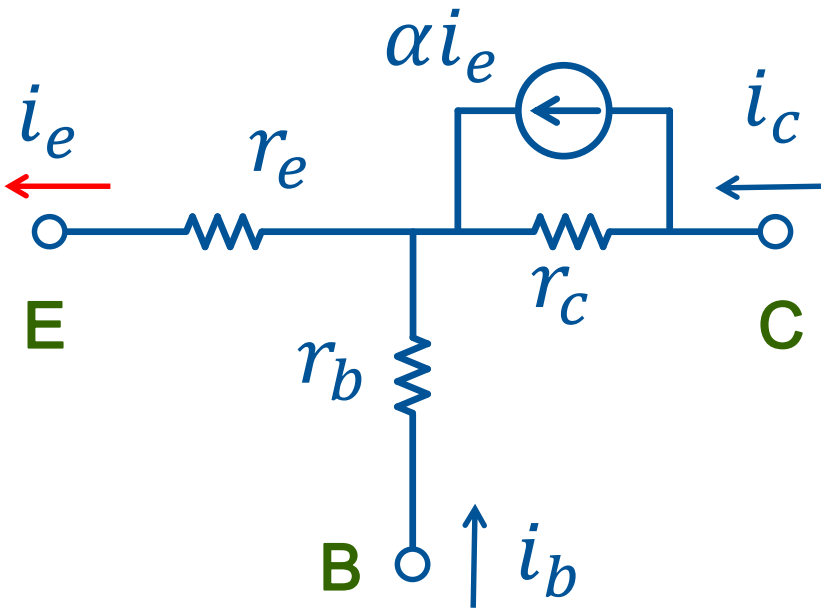


エミッタ接地

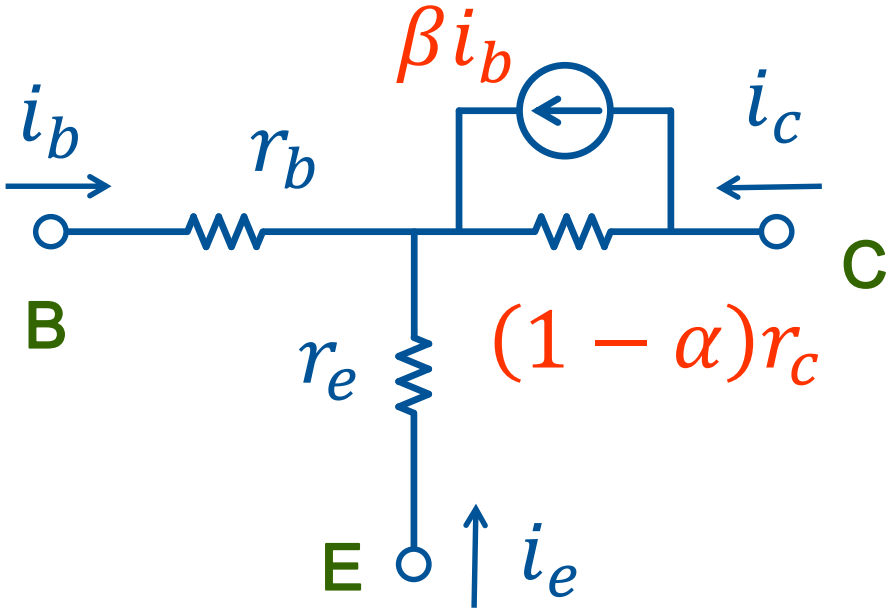
矢印の向き
表記ミス

等価回路（ベース接地・エミッタ接地）

revised



ベース接地



エミッタ接地

等価回路の変換

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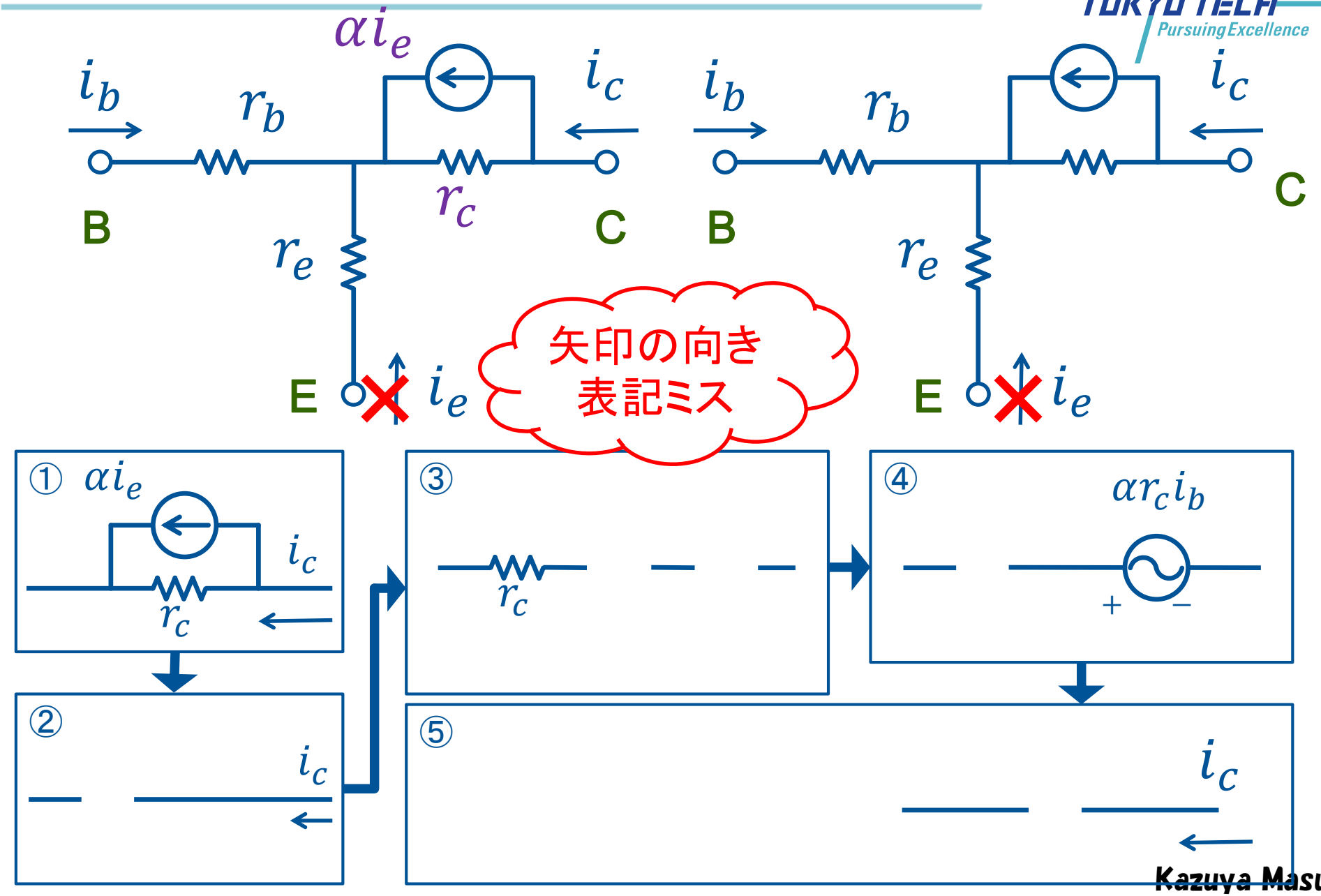

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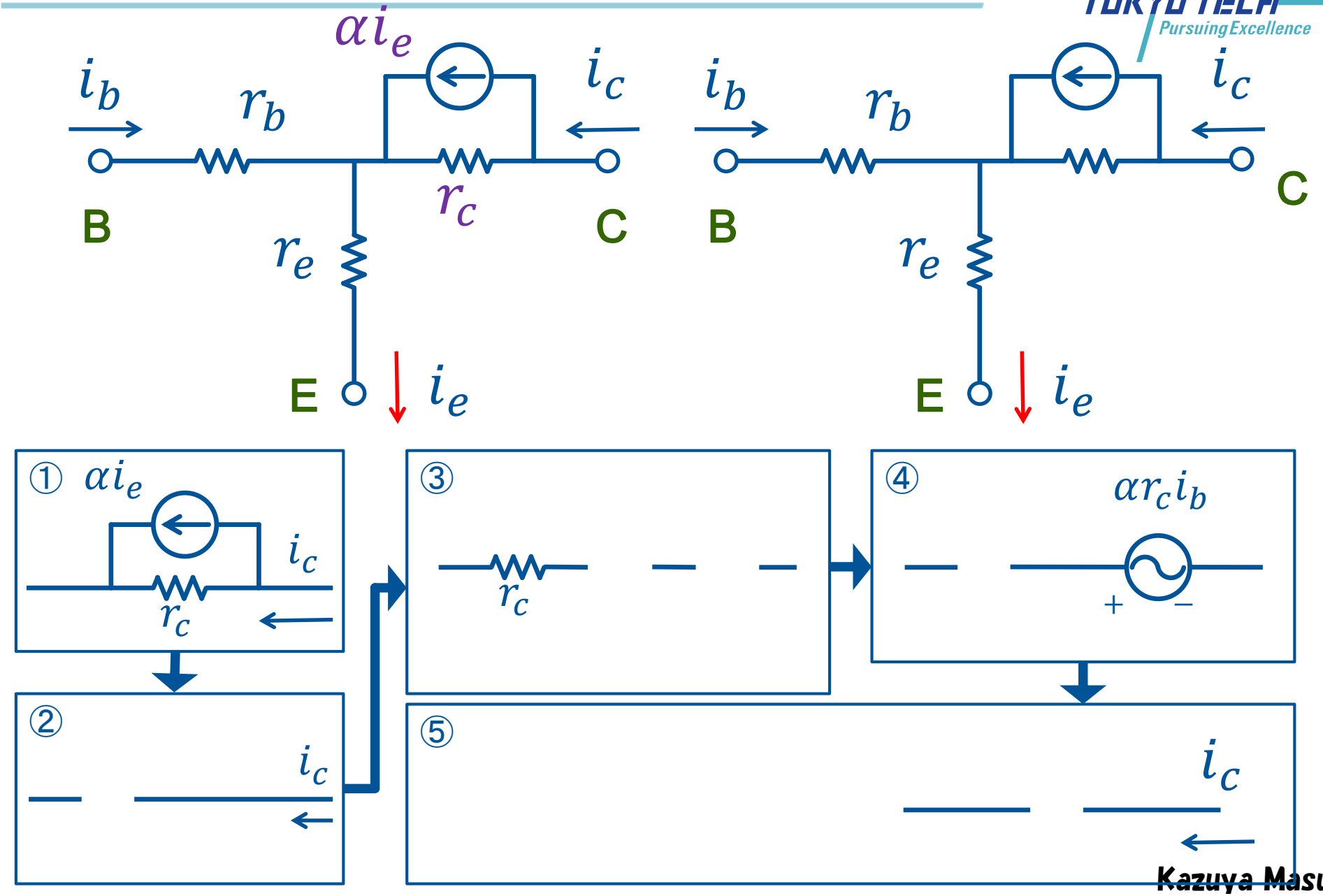
等価回路の変換


αi_e
i_b
r_b
i_c
r_c
B
C
r_e
E
i_e
i_b
r_b
i_c
B
C
r_e
E
i_e
①
αi_e
i_c
r_c
②
i_c
③
r_c
④
$\alpha r_c i_b$
+
−
⑤
i_c

小信号等価回路による増幅回路特性

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表 4.1　トランジスタ回路の小信号利得と入出力インピーダンス

形　　式	エミッタ接地	ベース接地	コレクタ接地
電流利得 G_i	$-\frac{\alpha}{1-\alpha}(=-\beta)$	α	$\frac{1}{1-\alpha}$
電圧利得 G_v	$-\frac{\alpha R_L}{r_e+(1-\alpha)r_b}$	$\frac{\alpha R_L}{r_e+(1-\alpha)r_b}$	$\frac{R_L}{r_e+(1-\alpha)r_b+R_L}$
電力利得 G_P	$\frac{\alpha^2 R_L}{(1-\alpha)\{r_e+(1-\alpha)r_b\}}$	$\frac{\alpha^2 R_L}{r_e+(1-\alpha)r_b}$	$\frac{R_L}{(1-\alpha)\{r_e+(1-\alpha)r_b+R_L\}}$
入力インピーダンス Z_i	$r_b+\frac{r_e}{1-\alpha}$	$r_e+(1-\alpha)r_b$	$r_b+\frac{r_E+R_L}{1-\alpha}$
出力インピーダンス Z_o	$r_c(1-\alpha)$	r_c	$r_e+(1-\alpha)(r_b+\rho)$*

*　信号源内部インピーダンス ρ の場合

各接地方式の特徴

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形　式	エミッタ接地	ベース接地	コレクタ接地
G_i	> 1	≤ 1	> 1
G_v	> 1	> 1	< 1
G_p	> 1	> 1	> 1
Z_i	中	小	大
Z_o	中	大	小
用途	電力増幅	電圧増幅	インピーダンス変換（出力バッファ）

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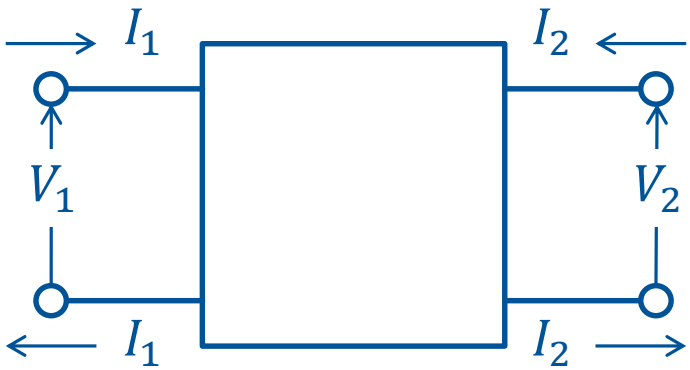
2-port parameters 四端子パラメータ



$$\begin{pmatrix} I_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix} \begin{pmatrix} V_1 \\ I_2 \end{pmatrix}$$

$$\begin{pmatrix} V_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} I_1 \\ V_2 \end{pmatrix}$$

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix}$$

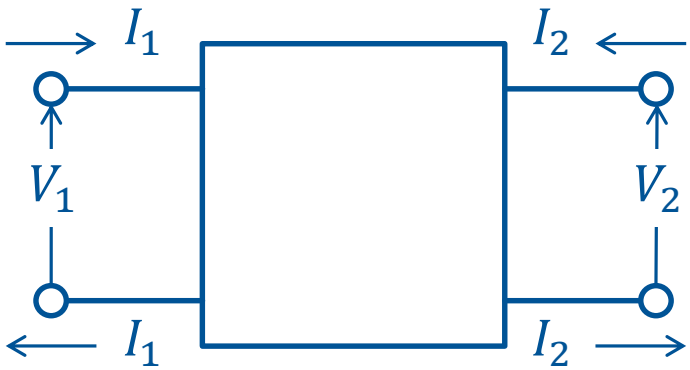
$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$$

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_2 \\ -I_2 \end{pmatrix}$$

$$\begin{pmatrix} V_2 \\ -I_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^{-1} \begin{pmatrix} V_1 \\ I_1 \end{pmatrix}$$

${}_4C_2 = 6$ 通りの組み合わせがある。

H (hybrid) parameter



$$\begin{pmatrix} V_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} I_1 \\ V_2 \end{pmatrix}$$

- $H_{11} = \left.\dfrac{V_1}{I_1}\right|_{V_2=0}$
- $H_{21} = \left.\dfrac{I_2}{I_1}\right|_{V_2=0}$

出力短絡

- $H_{12} = \left.\dfrac{V_1}{V_2}\right|_{I_1=0}$
- $H_{22} = \left.\dfrac{I_2}{V_2}\right|_{I_1=0}$

入力開放

トランジスタでは、hパラメータが容易に測定可能。
H-parameters are easily measurable parameters of bipolar transistor.

Relation between T-parameter and h-parameter

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$$\begin{pmatrix} h_{11B} & h_{12B} \\ h_{21B} & h_{22B} \end{pmatrix} = \begin{pmatrix} r_e + (1-\alpha)\dfrac{r_e r_c}{r_b + r_c} & \dfrac{r_b}{r_b + r_c} \\ -\dfrac{r_b + r_c \alpha}{r_b + r_c} \approx -\alpha & \dfrac{1}{r_b + r_c} \end{pmatrix} \quad \cdots ①$$

$$\begin{pmatrix} r_e = h_{11B} - \dfrac{h_{12B}(1 + h_{21B})(1 - h_{12B})}{h_{22B}} & r_b = \dfrac{h_{12B}}{h_{22B}} \\ \alpha = -\dfrac{h_{12B} + h_{21B}}{1 - h_{12B}} \approx -h_{21B} & r_c = \dfrac{1 - h_{12B}}{h_{22B}} \end{pmatrix} \quad \cdots ②$$

- For common-base circuit（ベース接地）

Relation between T-parameter and h-parameter

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$$\begin{pmatrix} h_{11E} & h_{12E} \\ h_{21E} & h_{22E} \end{pmatrix} = \begin{pmatrix} r_b + \dfrac{r_e r_c}{(1-\alpha)r_c + r_e} & \dfrac{r_e}{r_e + (1-\alpha)r_c} \\ \dfrac{\alpha r_c - r_e}{r_e + (1-\alpha)r_c} & \dfrac{1}{r_e + (1-\alpha)r_c} \end{pmatrix} \cdots ③$$

$$\left(\begin{array}{cc} r_e = \dfrac{h_{12E}}{h_{22E}} & r_b = h_{11E} - \dfrac{h_{12E}(1 + h_{21E})}{h_{22E}} \\ \alpha = \dfrac{h_{12E} + h_{21E}}{1 + h_{21E}} - h_{12B} & r_c = \dfrac{1 + h_{21E}}{h_{22E}} \end{array} \right) \cdots ④$$

- For common-emitter circuit（エミッタ接地）

What's next?

- Understanding of current-voltage characteristics of common-base, emitter, and collector.
- Understanding of small signal equivalent circuit.
- Today's circuit is just DC-characteristics. How is the RF characteristics? What determines the RF characteristics?

宿題

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- と云うことで、
- n^+pn^-接合
  - $N_E(emitter) = 1 \times 10^{19}(cm^{-3})$
  - $N_B(base) = 2 \times 10^{16}(cm^{-3})$
  - $N_C(collector) = 1 \times 10^{15}(cm^{-3})$
- について、
- $\phi_{E\mathrm{B}}, \phi_{B\mathrm{B}}, \phi_{C\mathrm{B}}$ および W_E, W_{BE}, W_{BC}, W_C を求めよ。

演習(宿題) 5月19日(月)まで。

- T形回路パラメータ(α、r_b、r_e、r_c)とベース接地hパラメータの関係(式①、②)を求めよ。
- T形回路パラメータ(α、r_b、r_e、r_c)とエミッタ接地hパラメータの関係(式③、④)を求めよ。
- 一般に、ベース接地等価回路のhパラメータを測定し、T形等価回路パラメータを用い、次にエミッタ接地hパラメータ求める。今、ベース接地のhパラメータが次のように測定された。T形等価回路パラメータとエミッタ接地hパラメータを求めよ。

$$\begin{pmatrix} h_{11B} & h_{12B} \\ h_{21B} & h_{22B} \end{pmatrix} = \begin{pmatrix} 25\ [\Omega] & 2.0 \times 10^{-4} \\ -0.98 & 0.4[\mu S] \end{pmatrix}$$