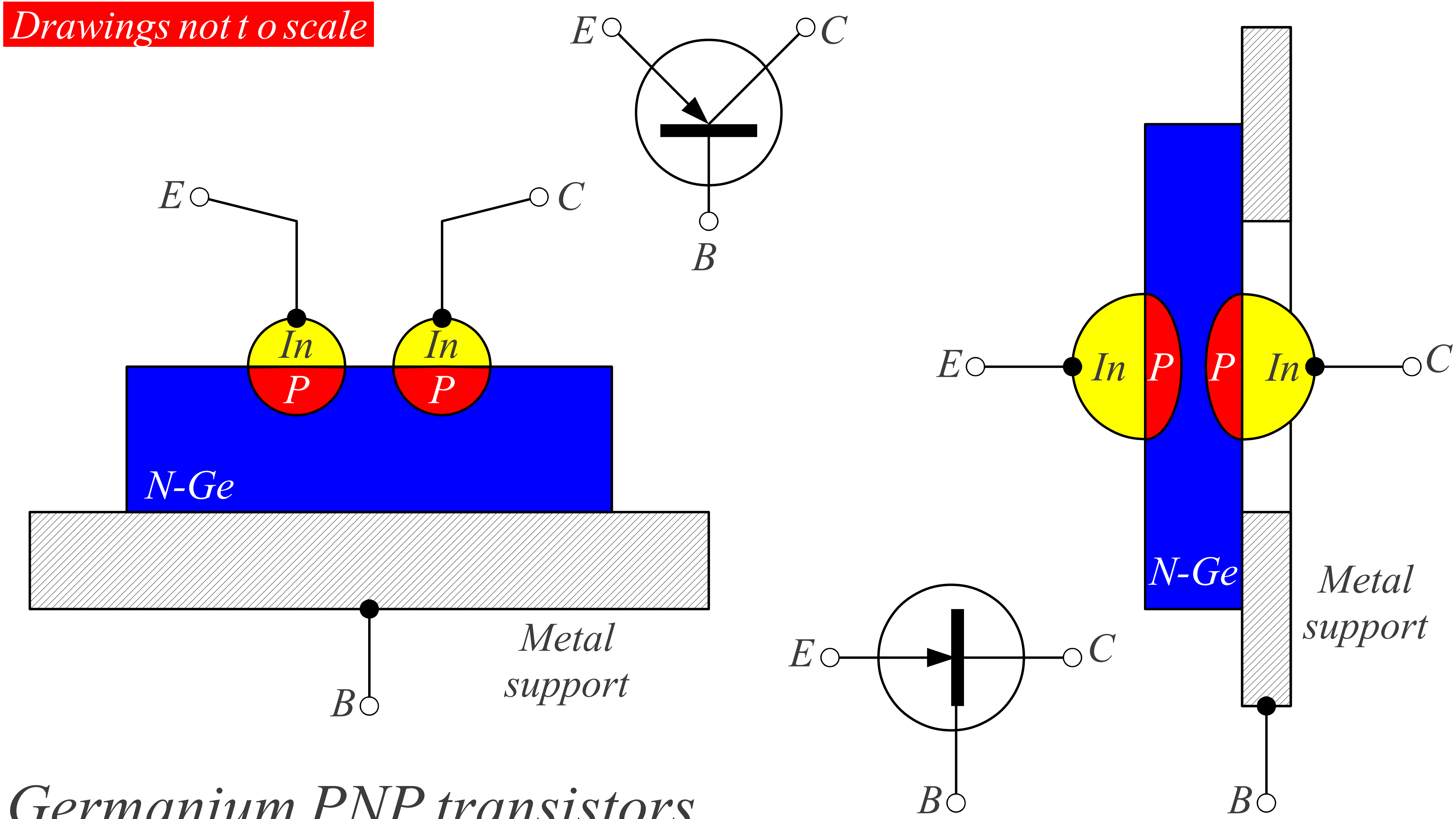
Communication Electronics

Lecture 6:

Semiconductor devices for communications - transistors



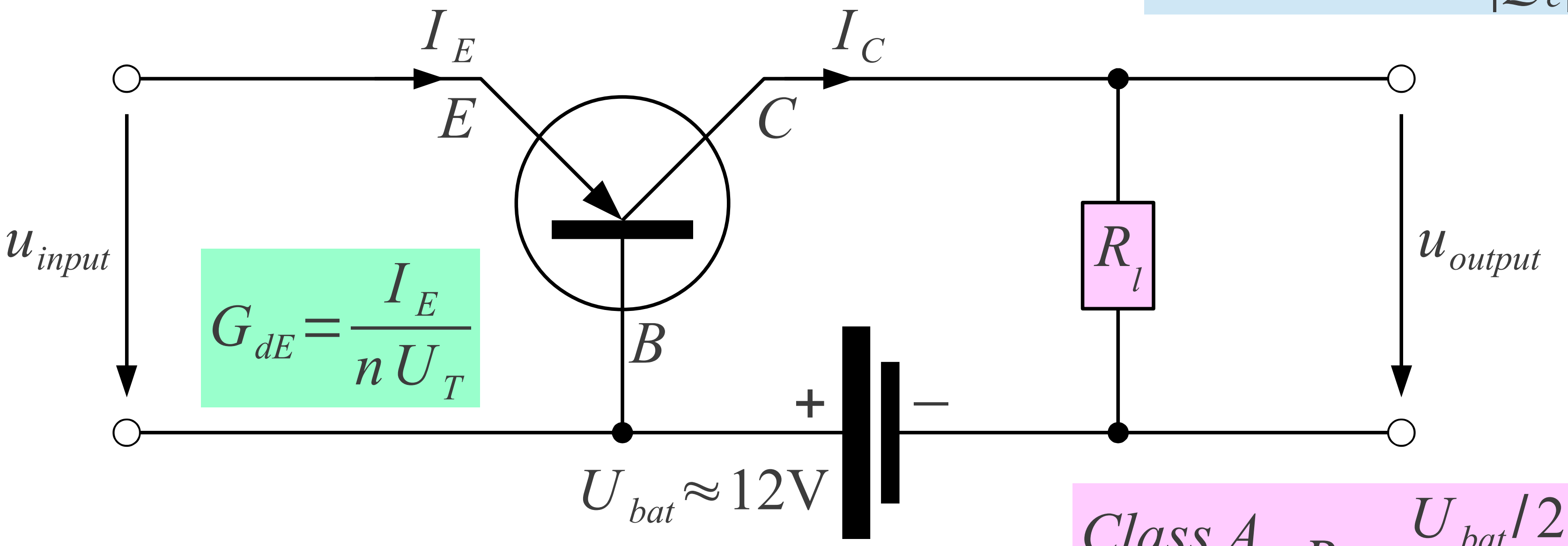
Germanium PNP transistors

$$A_I = \frac{d\,I_C}{d\,I_E} = \alpha < 1 \equiv \textit{current gain}$$

$$n \approx 1 \qquad U_T = \frac{k_B T}{|Q_e|} \approx 25\text{mV}$$

Old $\alpha \approx 0.9$

New $\alpha \approx 0.996$



$$G_{dE} = \frac{I_E}{n\,U_T}$$

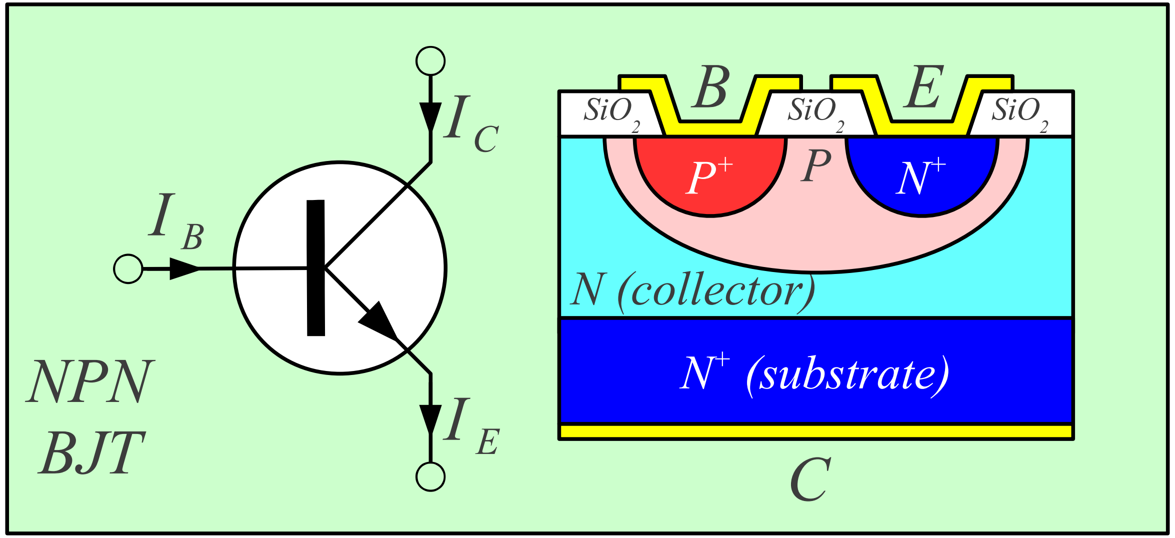
Class A bias $\quad R_l \approx \frac{U_{bat}/2}{I_C} = \frac{U_{bat}/2}{\alpha\,I_E}$

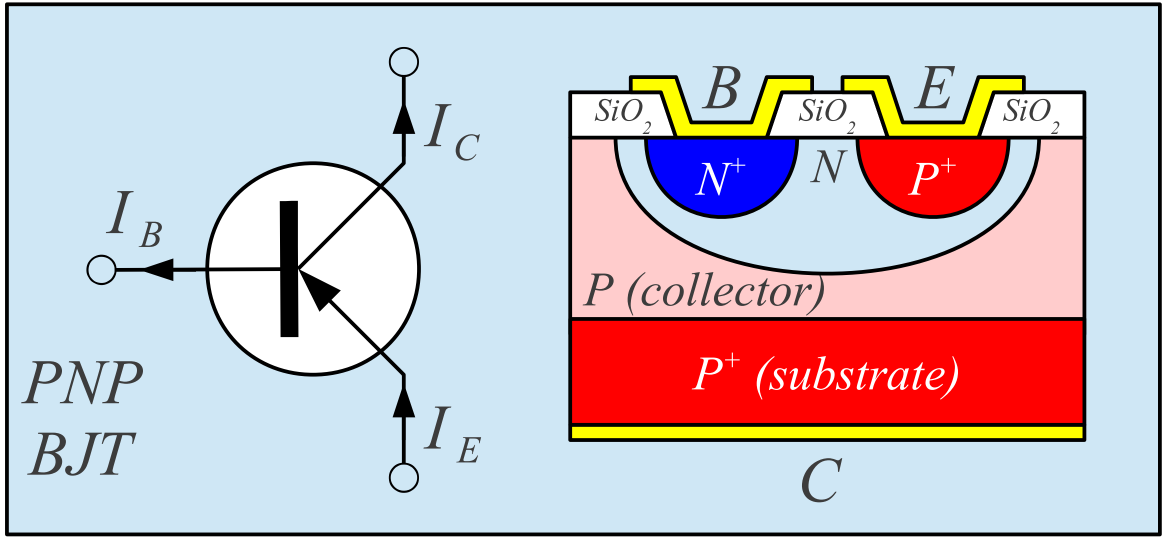
$$A_U = \frac{d\,u_{output}}{d\,u_{input}} = \frac{R_l}{R_{dE}} \cdot \frac{d\,I_C}{d\,I_E} = \alpha\,R_l\,G_{dE} \equiv \textit{voltage gain}$$

$$A_U \approx \alpha \cdot \frac{U_{bat}}{2\,\alpha\,I_E} \cdot \frac{I_E}{n\,U_T} = \frac{U_{bat}}{2\,n\,U_T} \approx 240$$

$$A_P = A_U \cdot A_I \approx 240 \cdot 0.9 = 216 \approx 23.3\text{dB} \equiv \textit{power gain}$$

Common − base amplifier





Drawings not t o scale

$$\frac{I_C}{I_B} = \beta \approx 250 \quad (30 \ldots 1000) \equiv common - emitter\ current\ gain$$

$$\beta = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha I_E}{I_E - \alpha I_E} = \frac{\alpha}{1-\alpha} = \frac{1}{\frac{1}{\alpha} - 1} \quad \leftrightarrow \quad \alpha = \frac{1}{1 + \frac{1}{\beta}} \approx 0.996 \quad (0.98 \ldots 0.999)$$

High $\beta \rightarrow$ *emitter doping* N^+ or $P^+ \gg$ *base doping P* or *N*

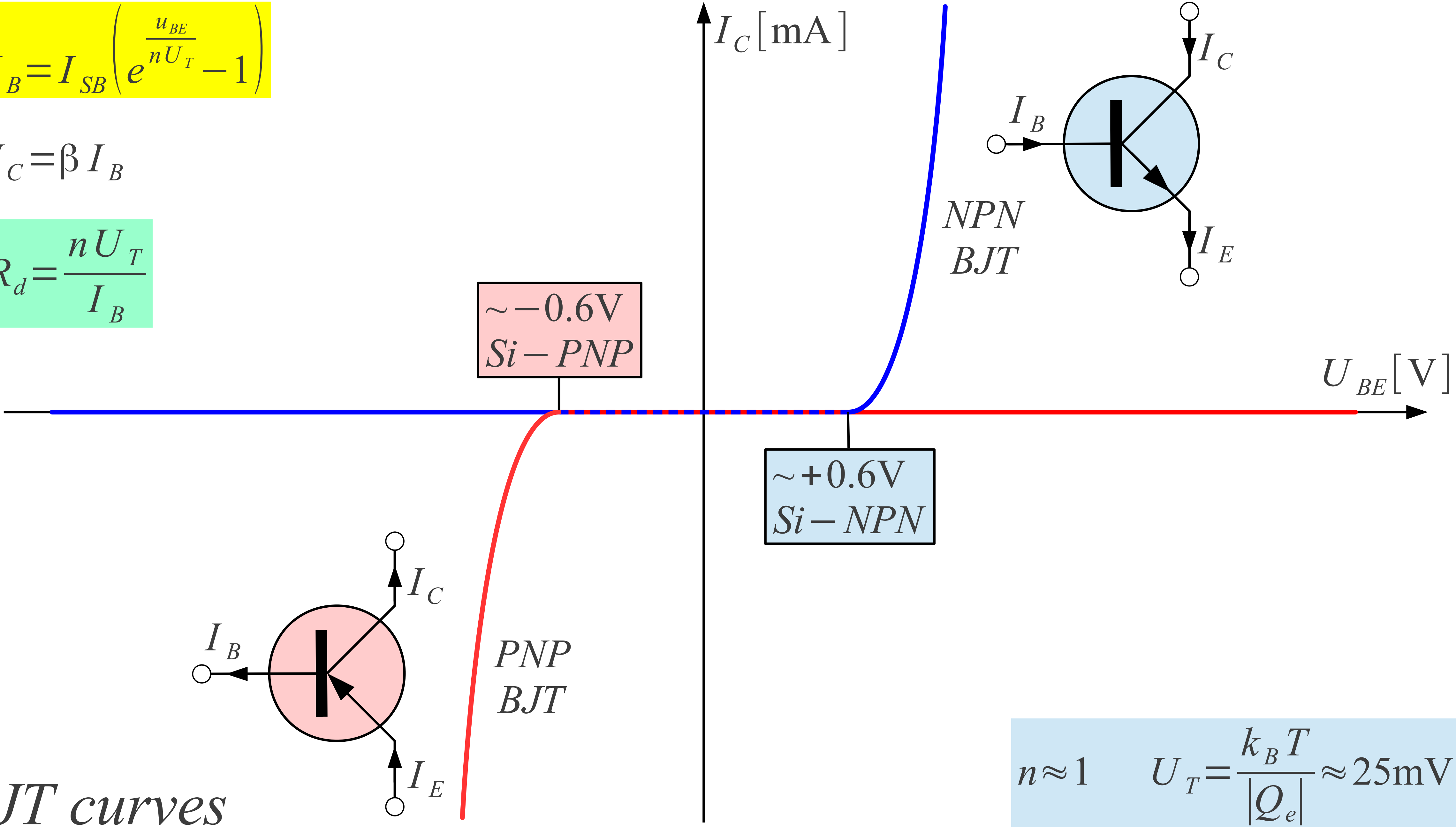
BE reverse breakdown
3V ... 15V
long – term destructive !

Planar silicon bipolar transistors

$$I_B = I_{SB}\left(e^{\frac{u_{BE}}{nU_T}} - 1\right)$$

$$I_C = \beta I_B$$

$$R_d = \frac{nU_T}{I_B}$$

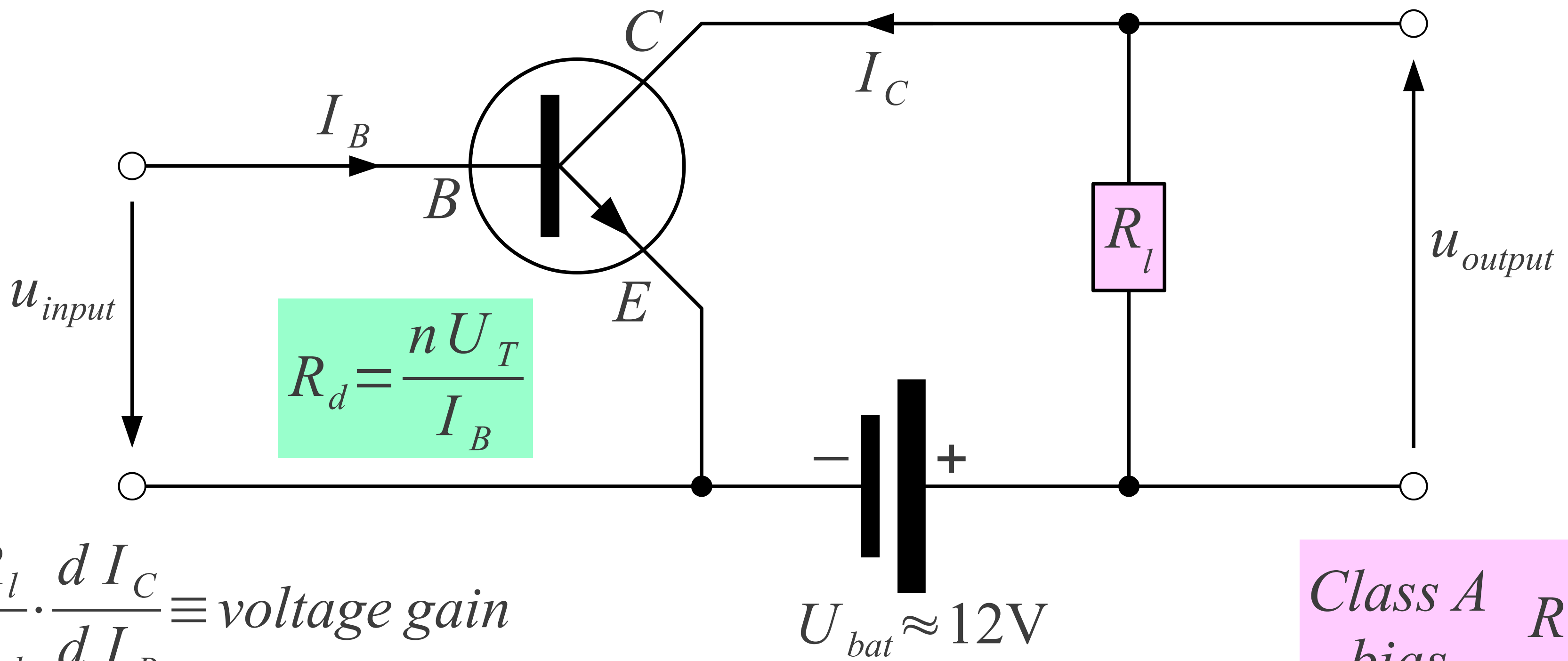


$$n \approx 1 \qquad U_T = \frac{k_B T}{|Q_e|} \approx 25\text{mV}$$

BJT curves

$$A_I = \frac{d\,I_C}{d\,I_B} = \beta \approx 250 \equiv \textit{current gain}$$

$$n \approx 1 \qquad U_T = \frac{k_B T}{|Q_e|} \approx 25\text{mV}$$



$$R_d = \frac{n\,U_T}{I_B}$$

$$A_U = \frac{d\,u_{output}}{d\,u_{input}} = \frac{R_l}{R_d} \cdot \frac{d\,I_C}{d\,I_B} \equiv \textit{voltage gain}$$

Class A bias $\quad R_l \approx \frac{U_{bat}/2}{I_C}$

$$A_U \approx \frac{U_{bat}}{2\,I_C} \cdot \frac{I_B}{n\,U_T} \cdot \beta = \frac{U_{bat}}{2\,n\,U_T} \approx 240$$

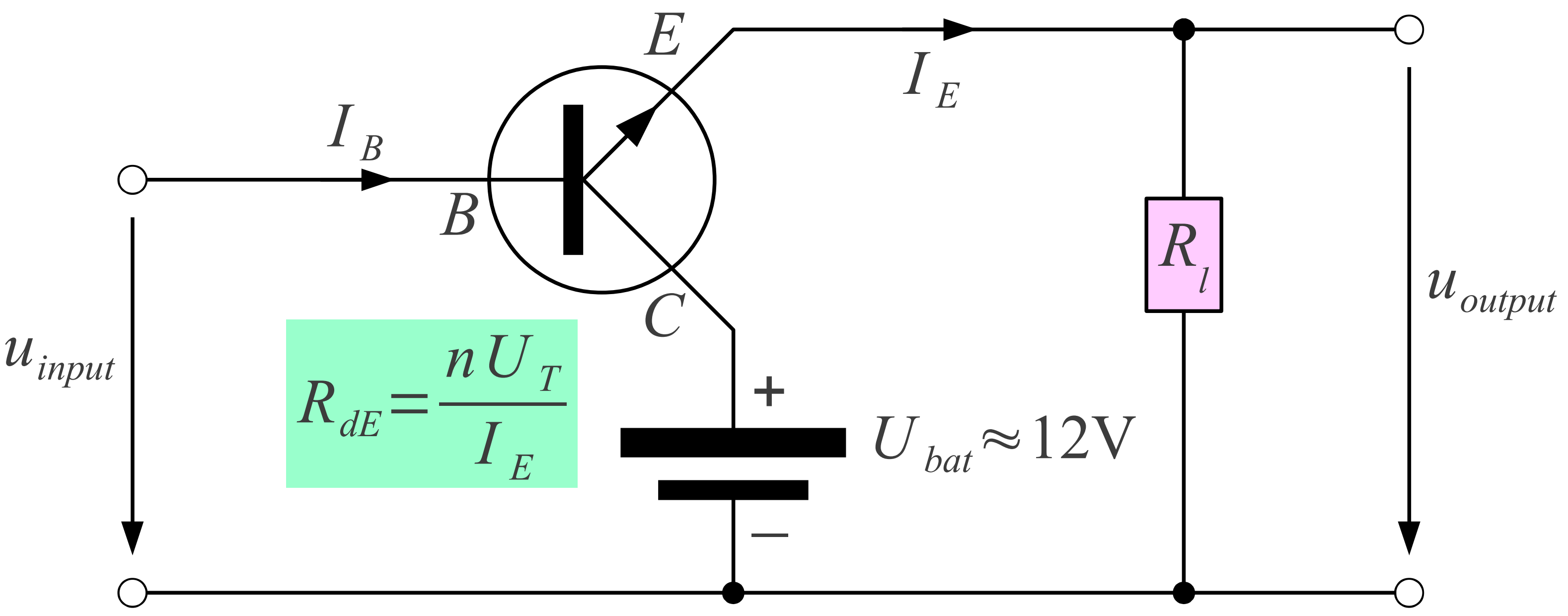
$$A_P = A_U \cdot A_I \approx 240 \cdot 250 = 60000 \approx 47.8\text{dB} \equiv \textit{power gain}$$

Common − emitter amplifier

$$A_I = \frac{d\,I_E}{d\,I_B} = \beta + 1 \approx 251 \equiv \textit{current gain}$$

$$n \approx 1 \qquad U_T = \frac{k_B T}{|Q_e|} \approx 25\text{mV}$$

Class A bias $\quad R_l \approx \frac{U_{bat}/2}{I_E}$



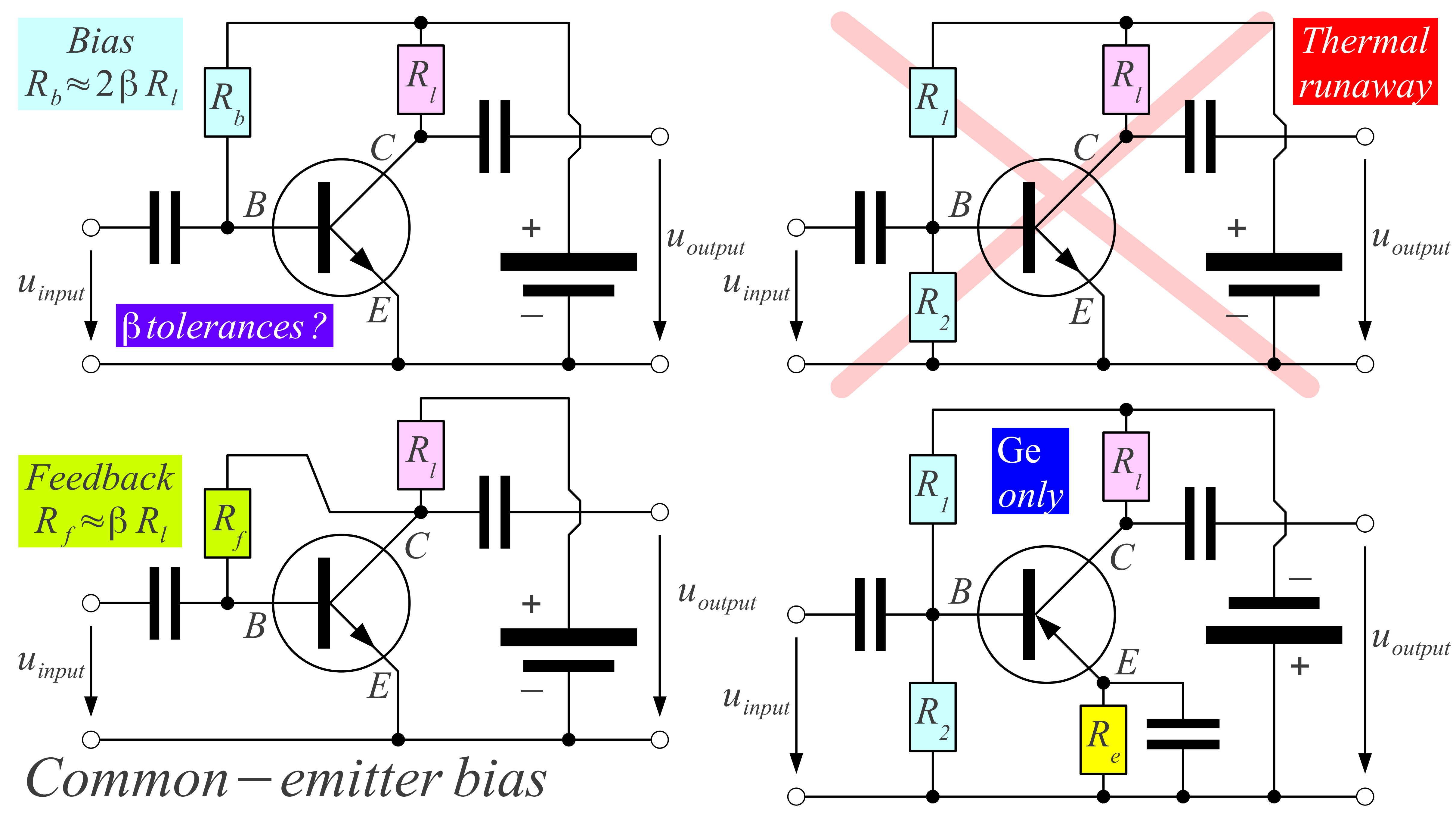
$$R_{dE} = \frac{n\,U_T}{I_E}$$

$$A_U = \frac{d\,u_{output}}{d\,u_{input}} = \frac{R_l}{R_{dE} + R_l} \equiv \textit{voltage gain}$$

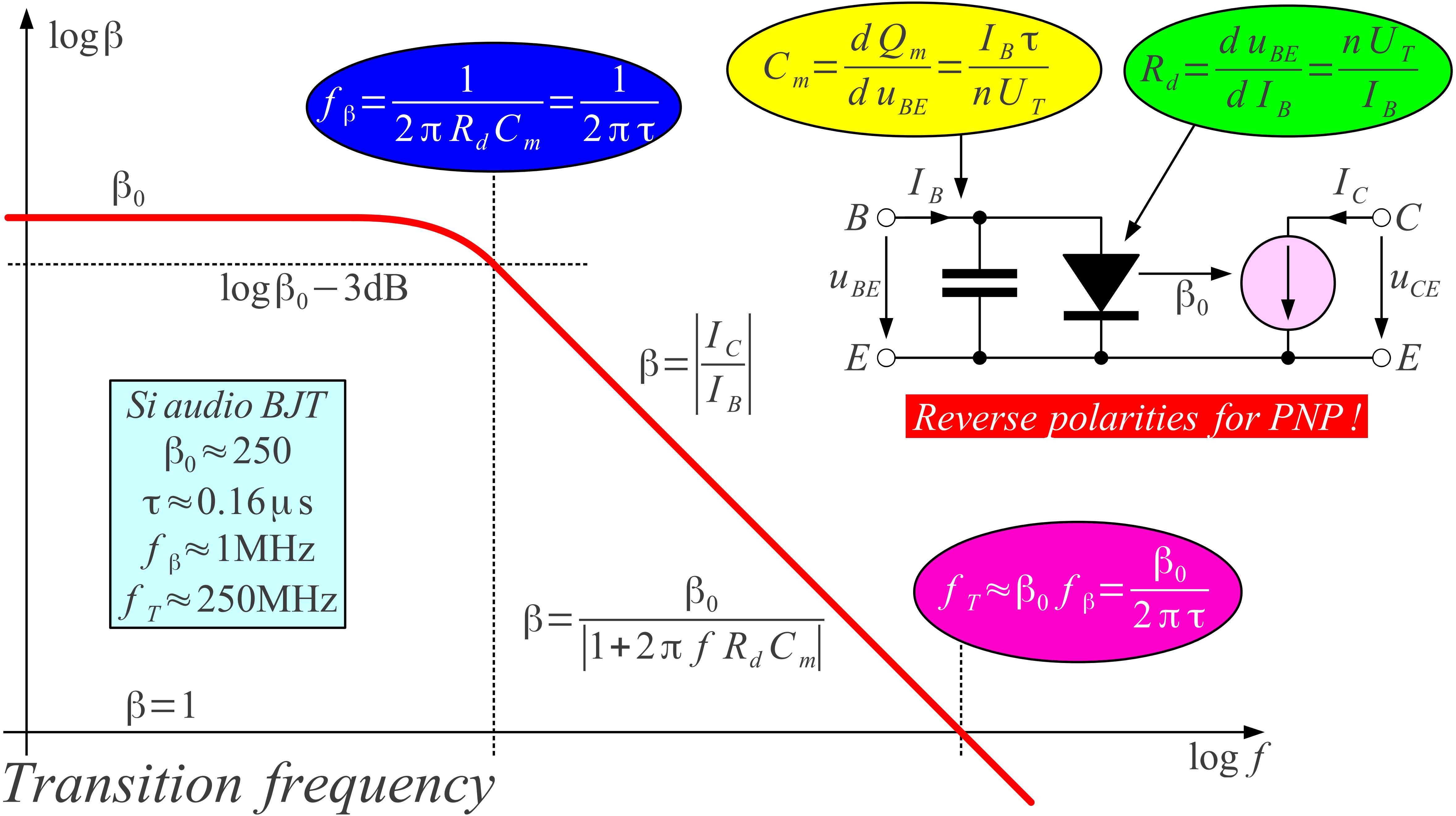
$$A_P = A_U \cdot A_I \approx 0.996 \cdot 251 \approx 250 \approx 24.0\text{dB} \equiv \textit{power gain}$$

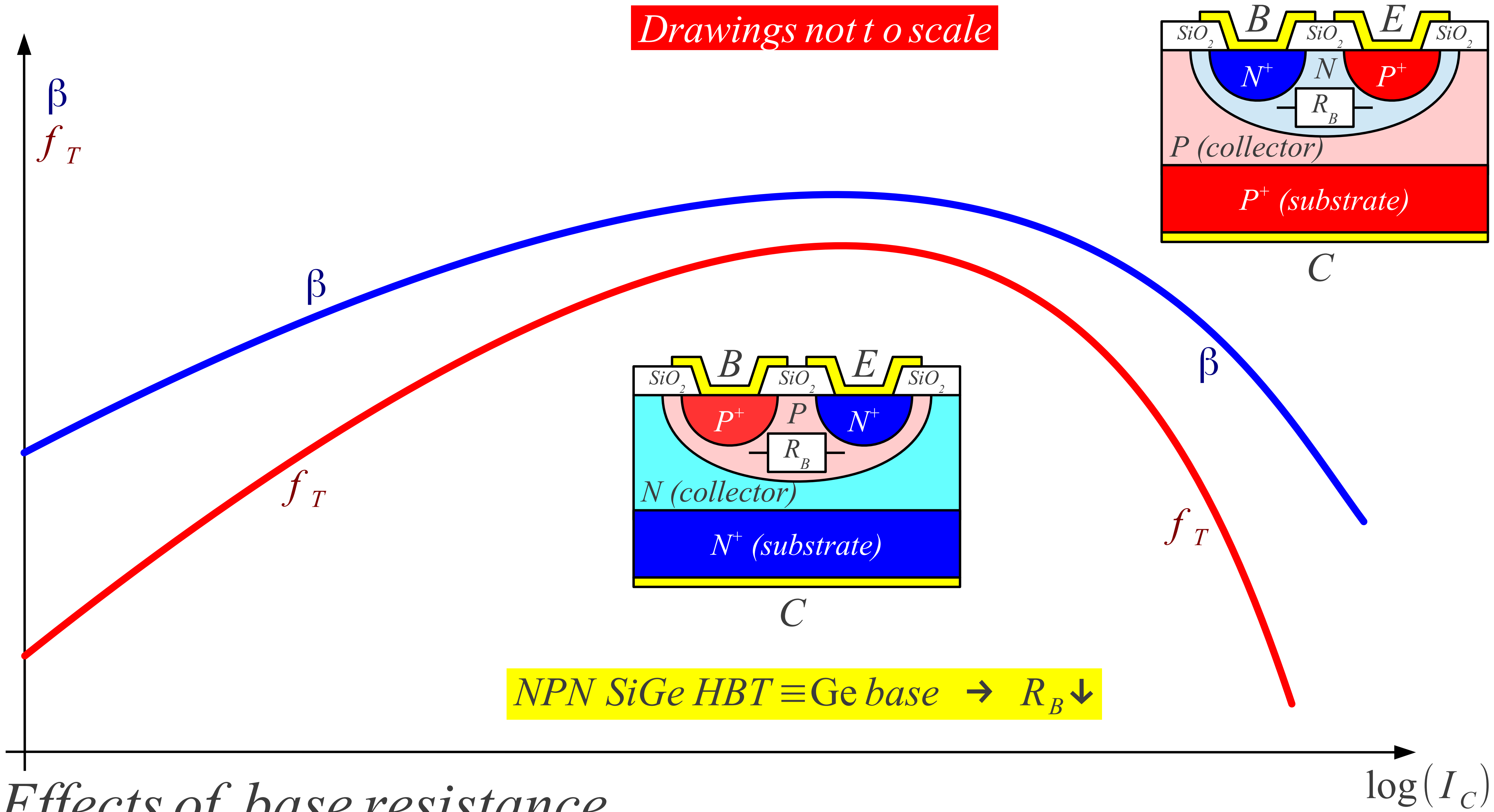
$$A_U = \frac{1}{\frac{R_{dE}}{R_l} + 1} = \frac{1}{\frac{2\,n\,U_T}{U_{bat}} + 1} \approx \frac{1}{\frac{1}{240} + 1} \approx 0.996$$

Emitter follower


Bias
R_b ≈ 2 β R_l
R_b
R_l
C
B
E
+
–
u_input
u_output
β tolerances ?
Thermal runaway
R_1
R_2
Feedback
R_f ≈ β R_l
R_f
Ge only
R_e
Common – emitter bias

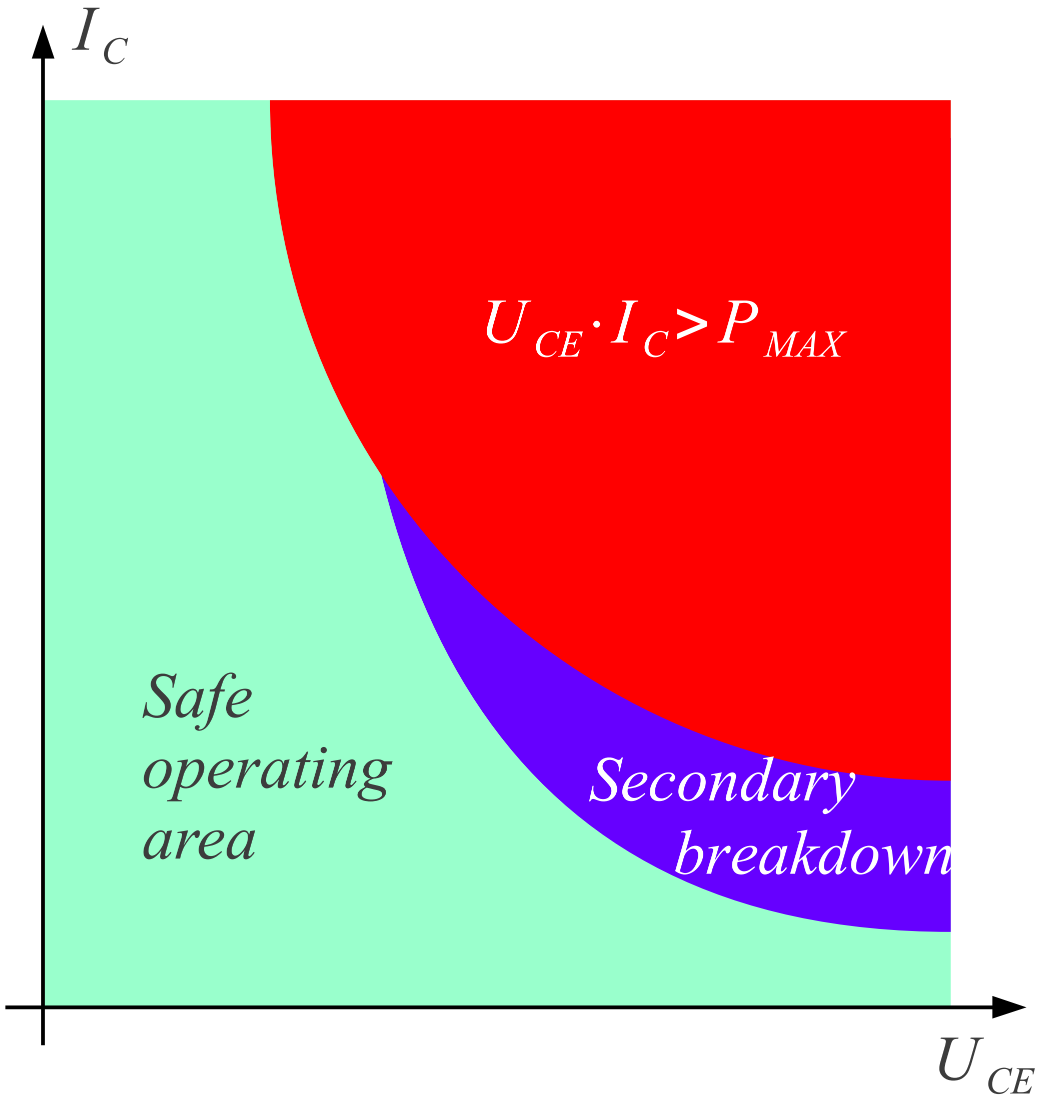
Transition frequency

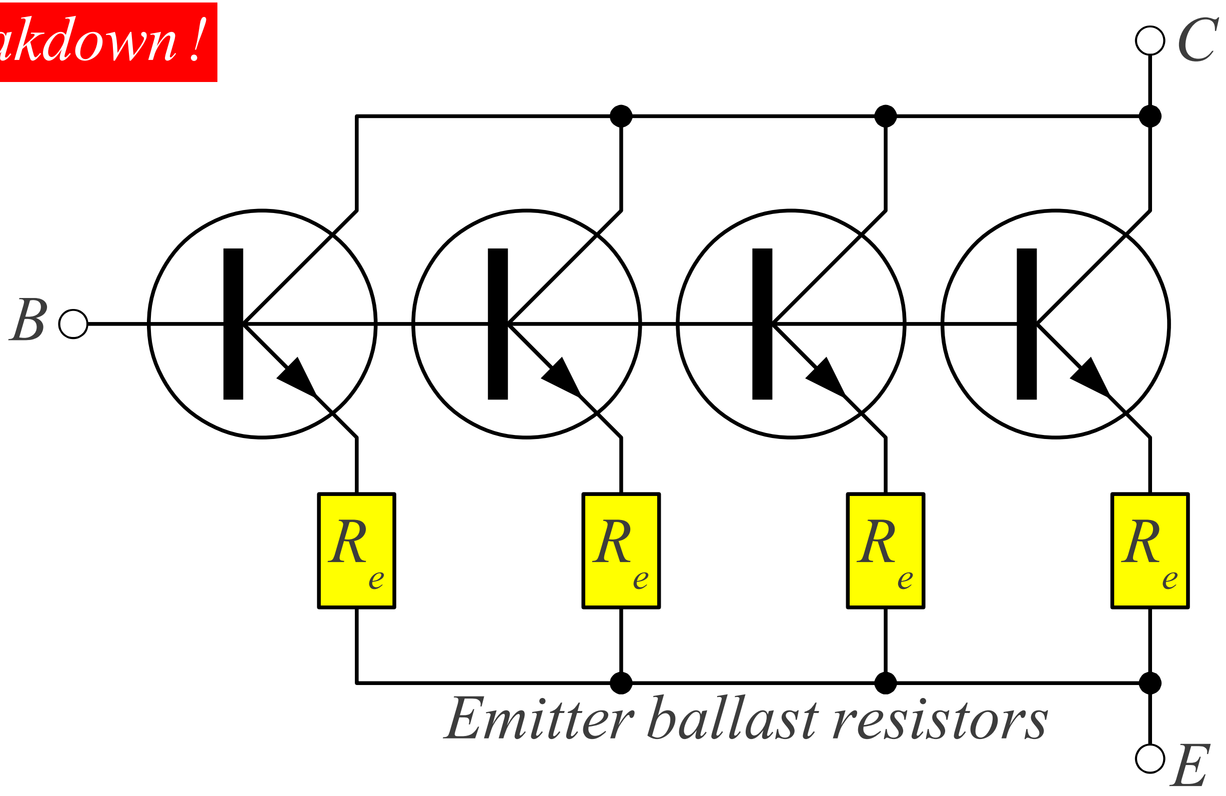




Effects of base resistance

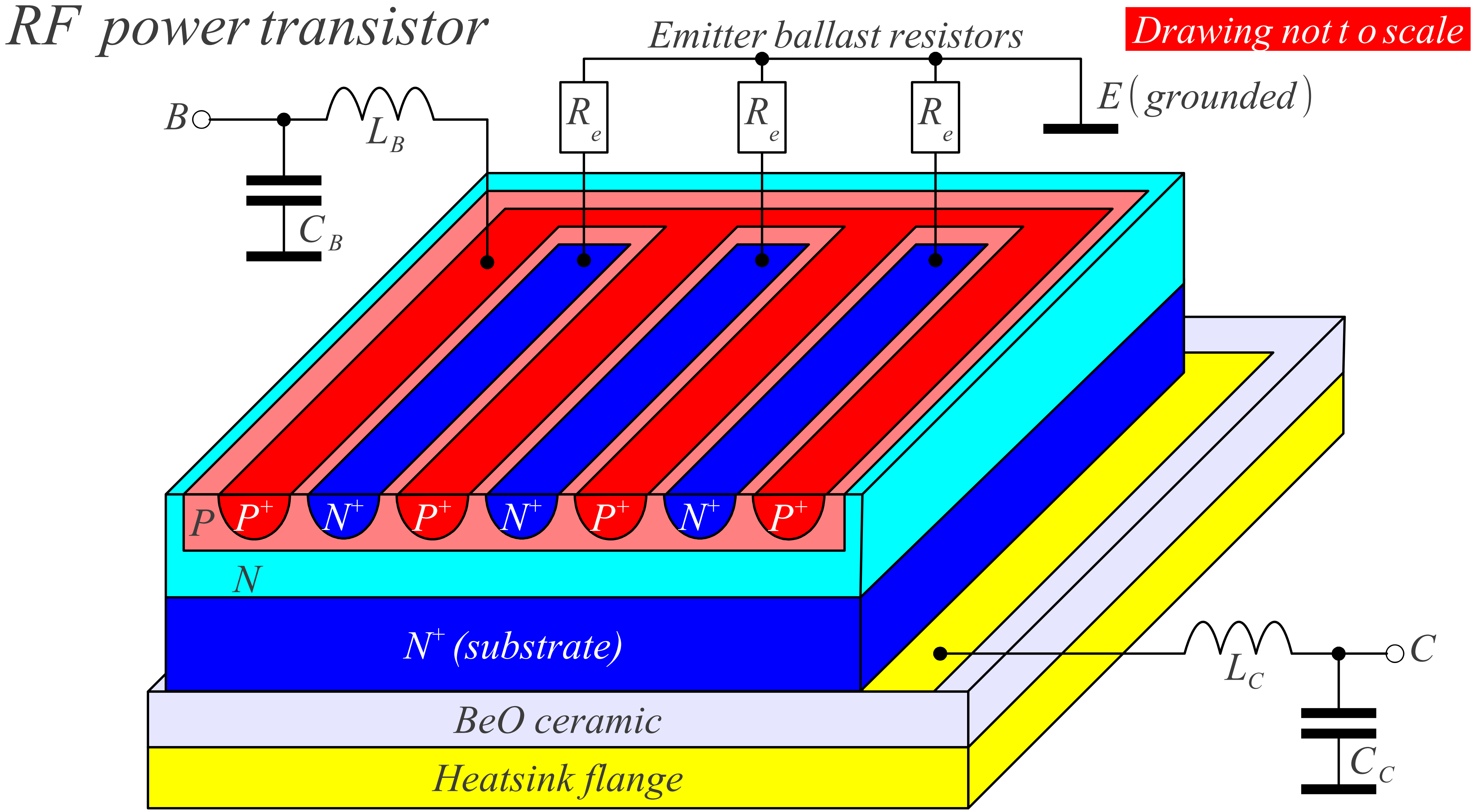
U_{BE} $TC<0$ → Secondary breakdown !





RF transistors f~1GHz	
Small-signal	Power ~10W
~10 emitters	~1000 emitters

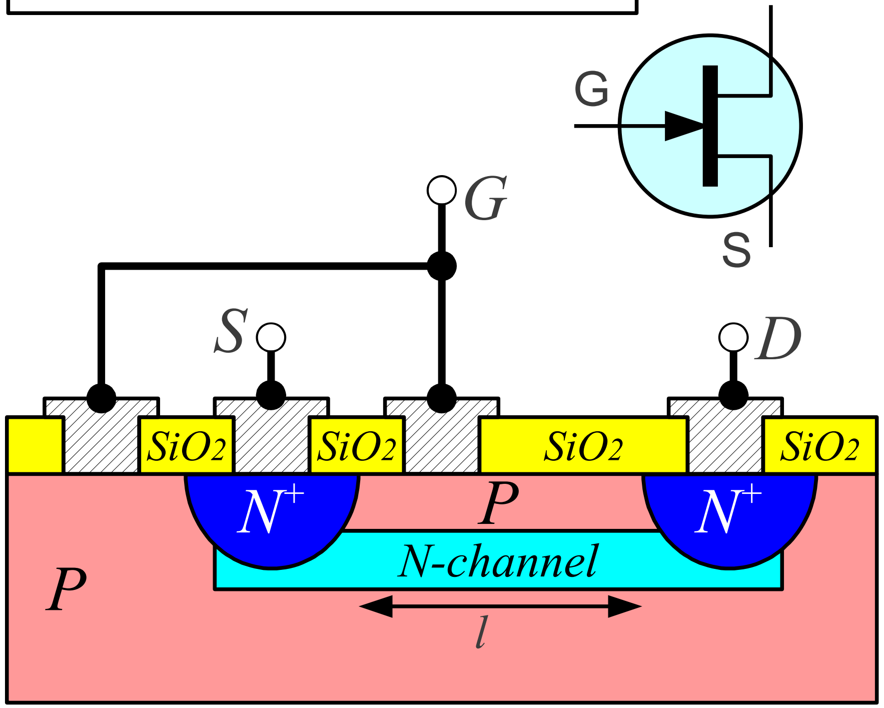
Secondary breakdown


RF power transistor
Emitter ballast resistors
Drawing not t o scale
B
L_B
C_B
R_e
R_e
R_e
E (grounded)
P
P+
N+
P+
N+
P+
N+
P+
N
N+ (substrate)
BeO ceramic
Heatsink flange
L_C
C
C_C

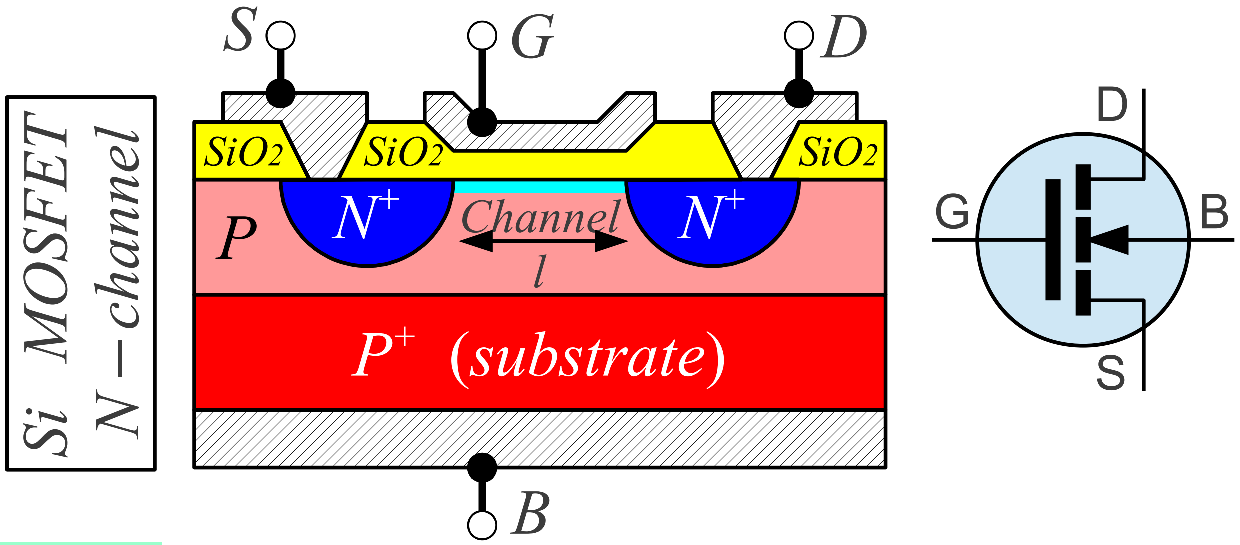
1970: $l_{channel} \approx 10\mu m \rightarrow f \approx 100MHz$

2020: $l_{channel} \approx 10nm \rightarrow f \approx 100GHz$

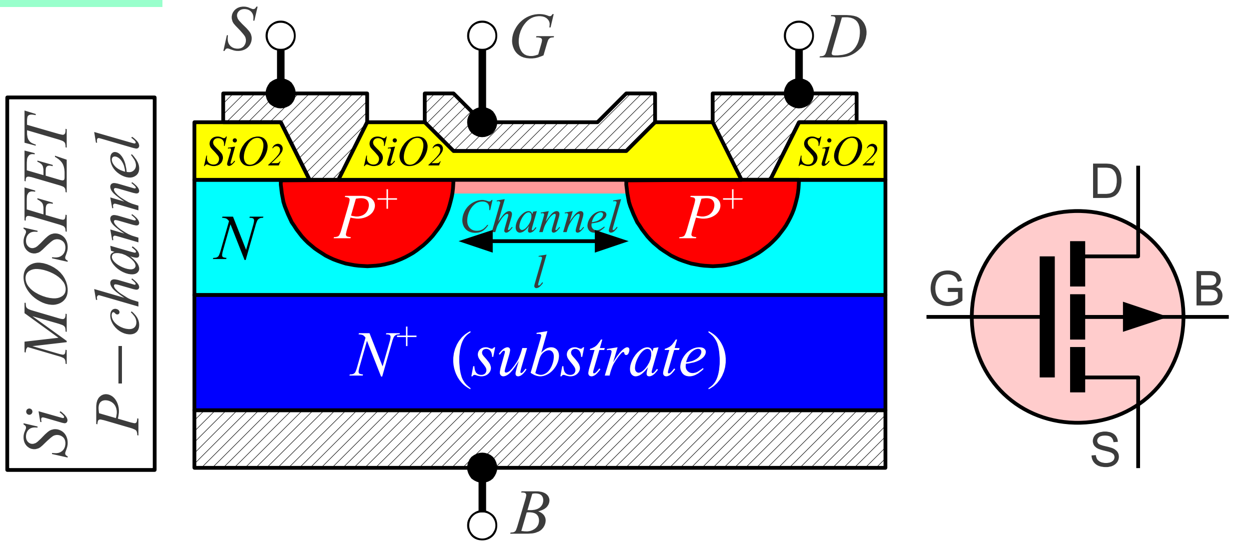
Si N – channel JFET



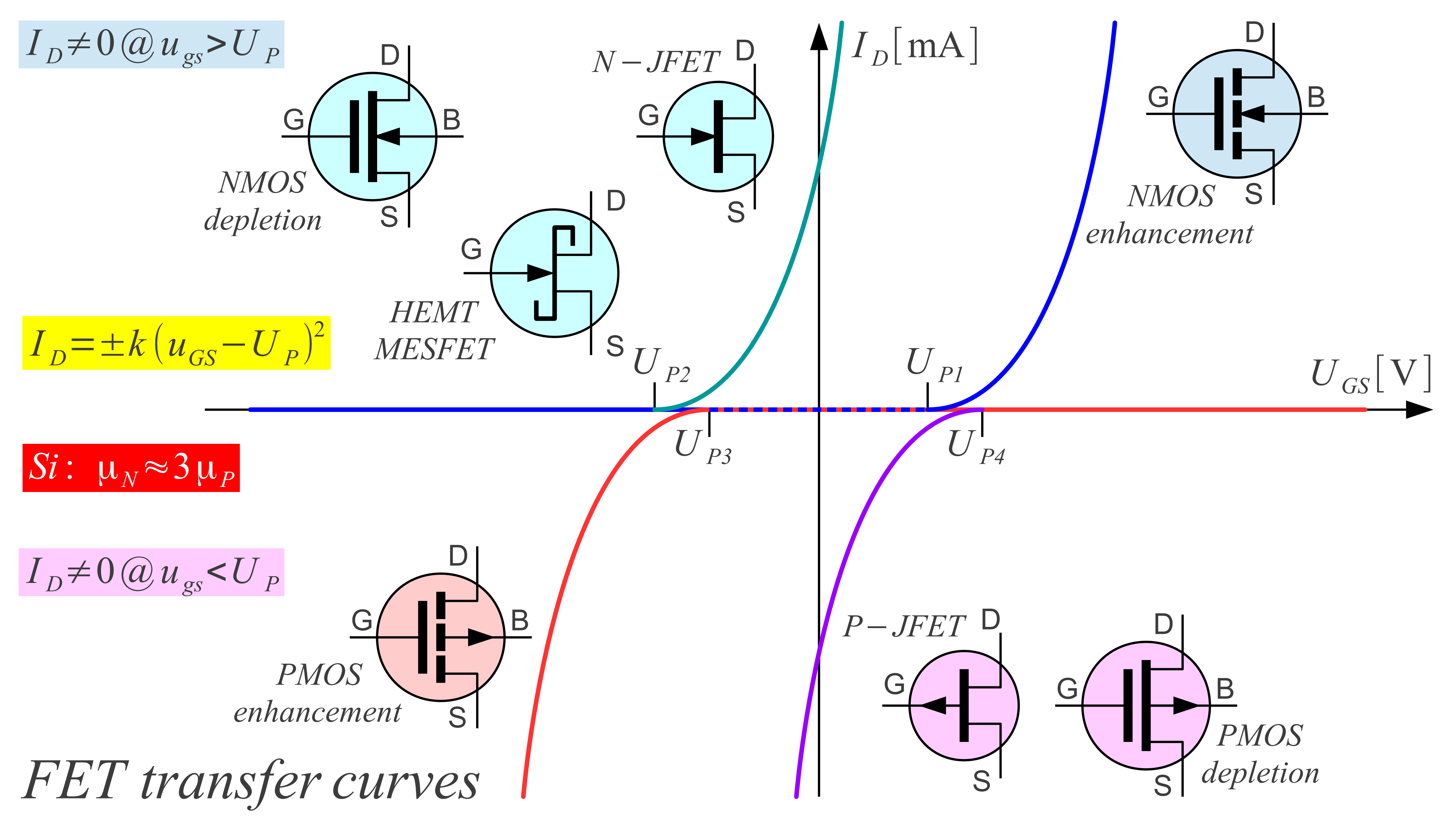
Small – signal transistors



Drawings not to scale

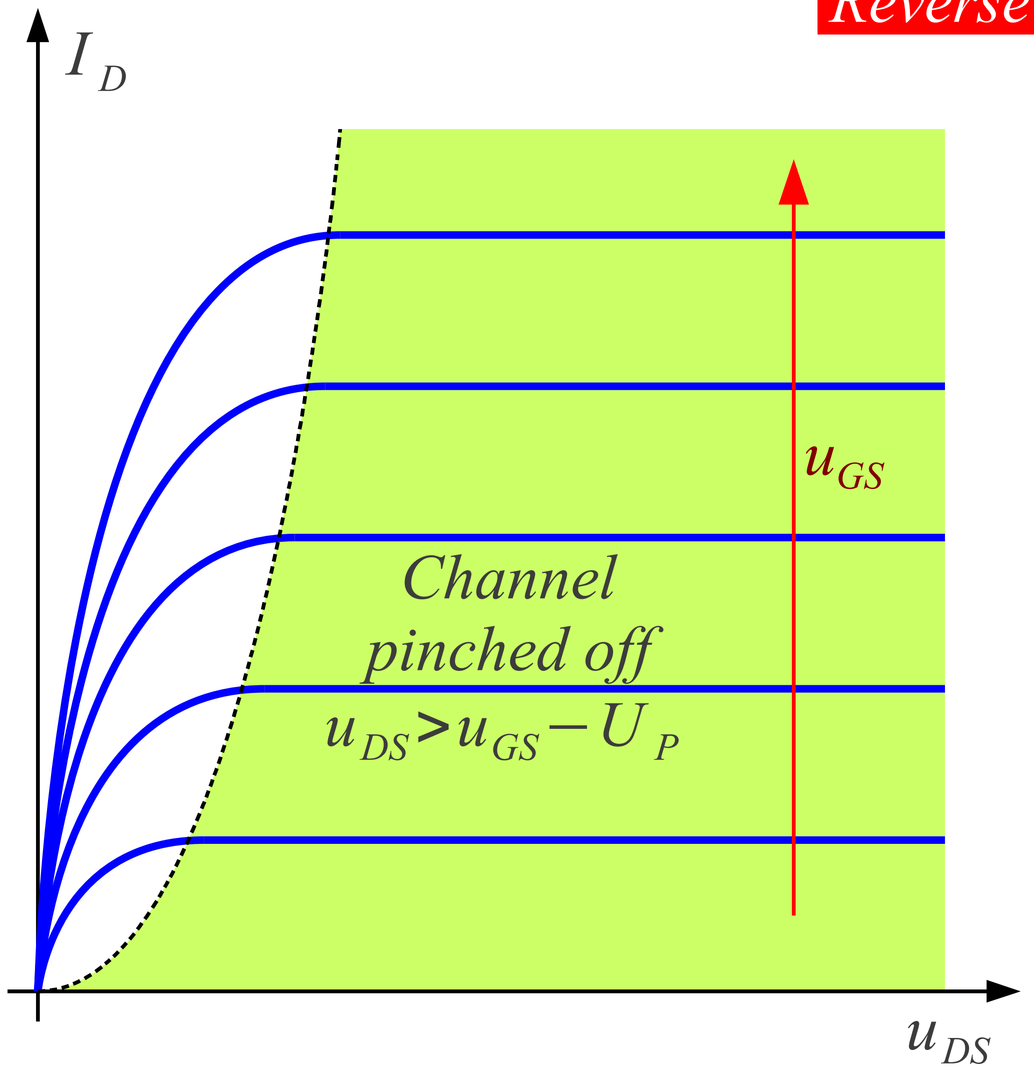


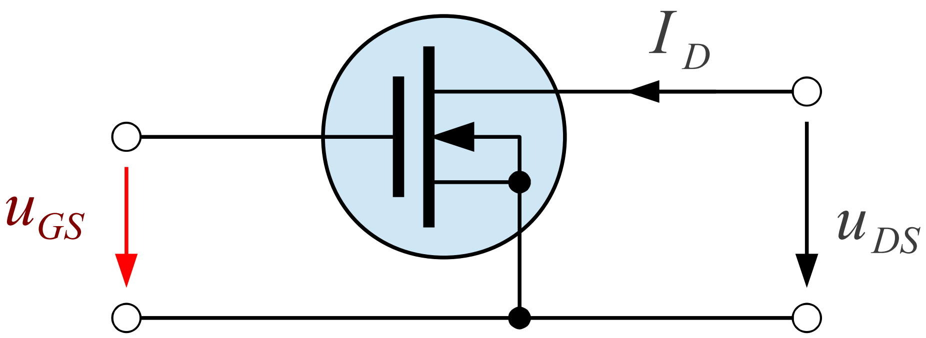
Field – effect transistors

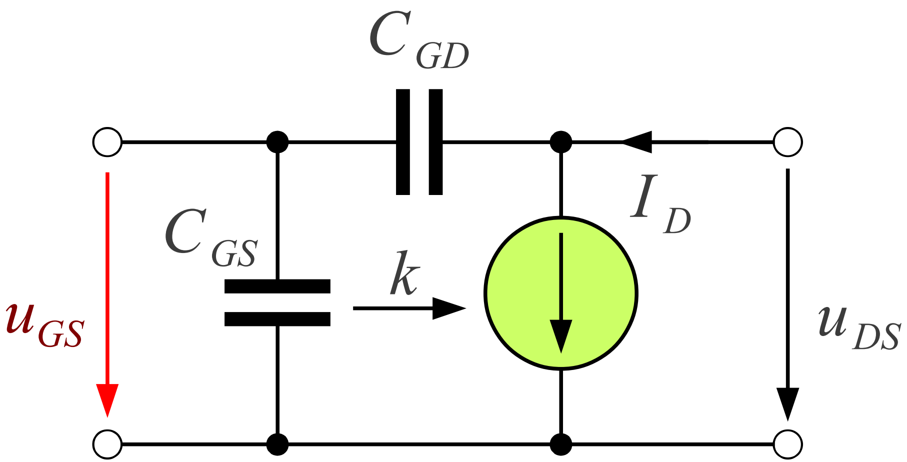


$I_D \neq 0 @ u_{gs} > U_P$
NMOS depletion
G
D
B
S
N−JFET
G
D
S
HEMT MESFET
G
D
S
$I_D [mA]$
NMOS enhancement
G
D
B
S
$I_D = \pm k (u_{GS} - U_P)^2$
U_{P2}
U_{P1}
$U_{GS} [V]$
U_{P3}
U_{P4}
$Si: \mu_N \approx 3\mu_P$
$I_D \neq 0 @ u_{gs} < U_P$
PMOS enhancement
G
D
B
S
P−JFET
G
D
S
PMOS depletion
G
D
B
S
FET transfer curves

Reverse polarities for P channel !







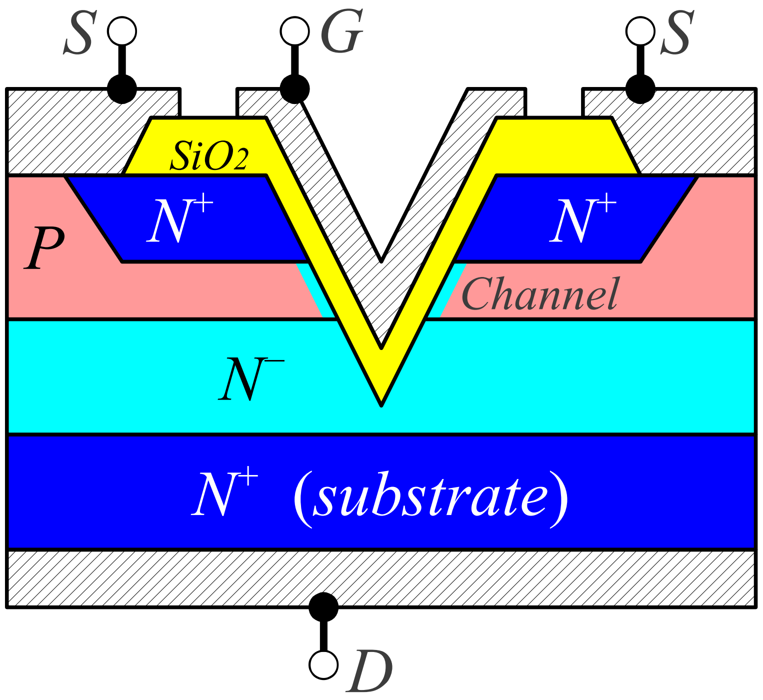
FET output curves

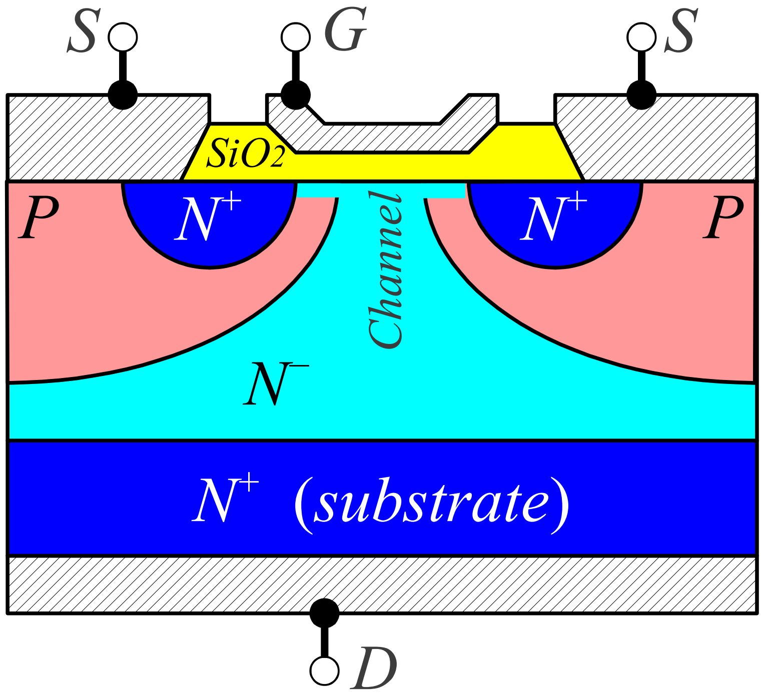
Drawings not to scale

$R_{channel}$ TC>0 →
NO secondary breakdown !

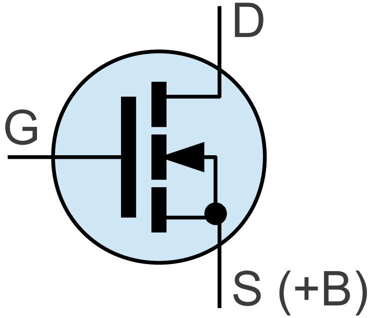
|| operation of
thousands of transistors

VMOS

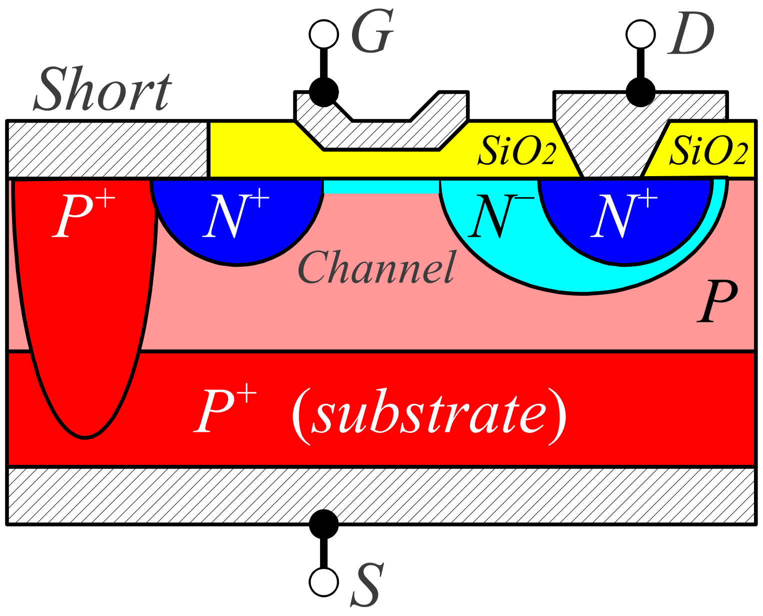




Power MOS

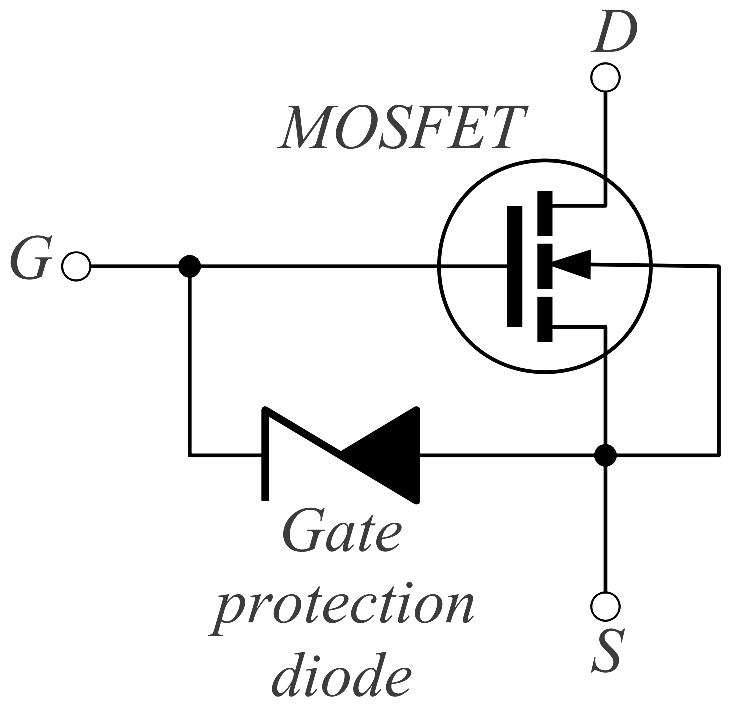


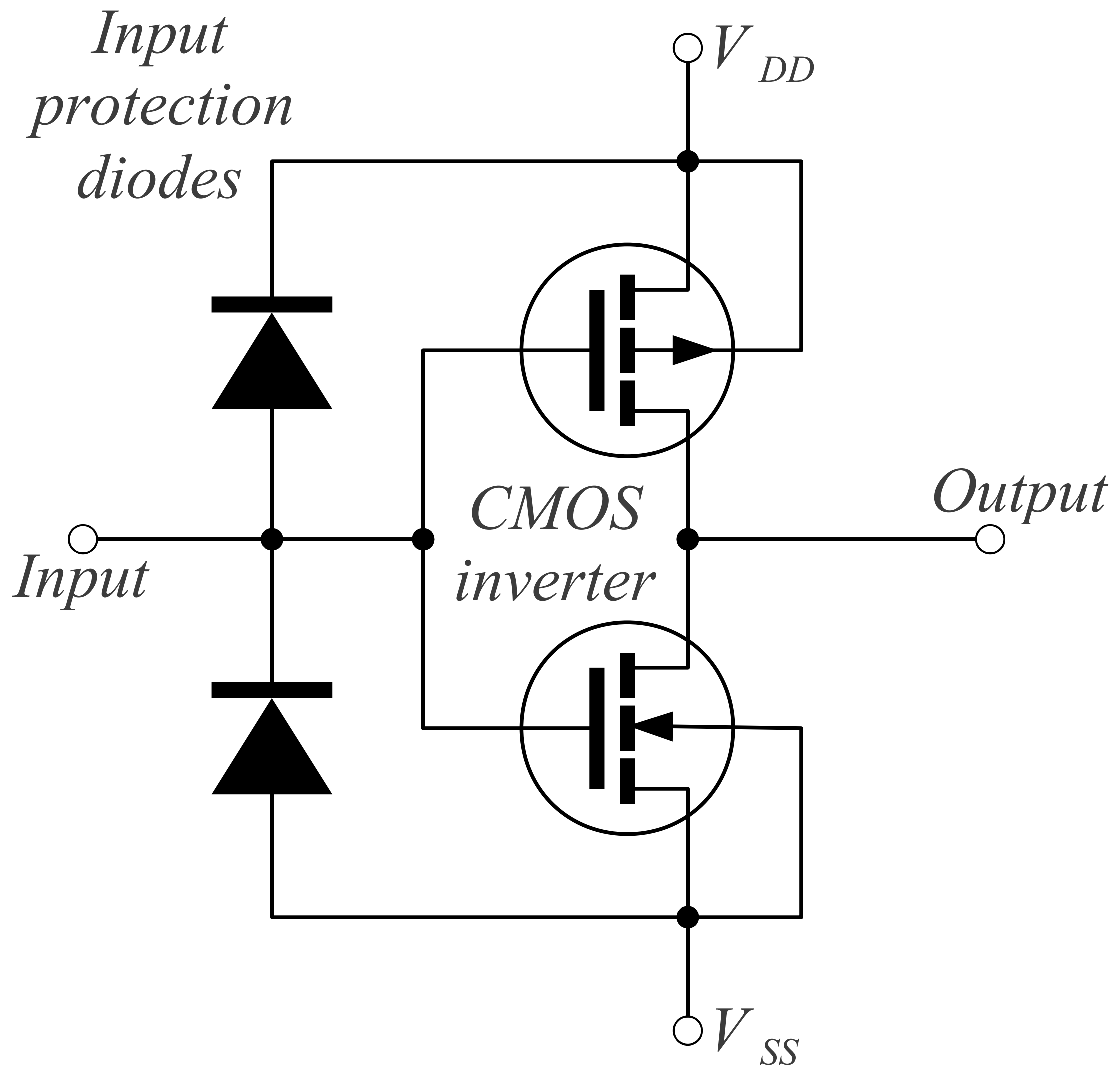
RF LDMOS



Power MOSFETs

Side effects of protection diodes ?



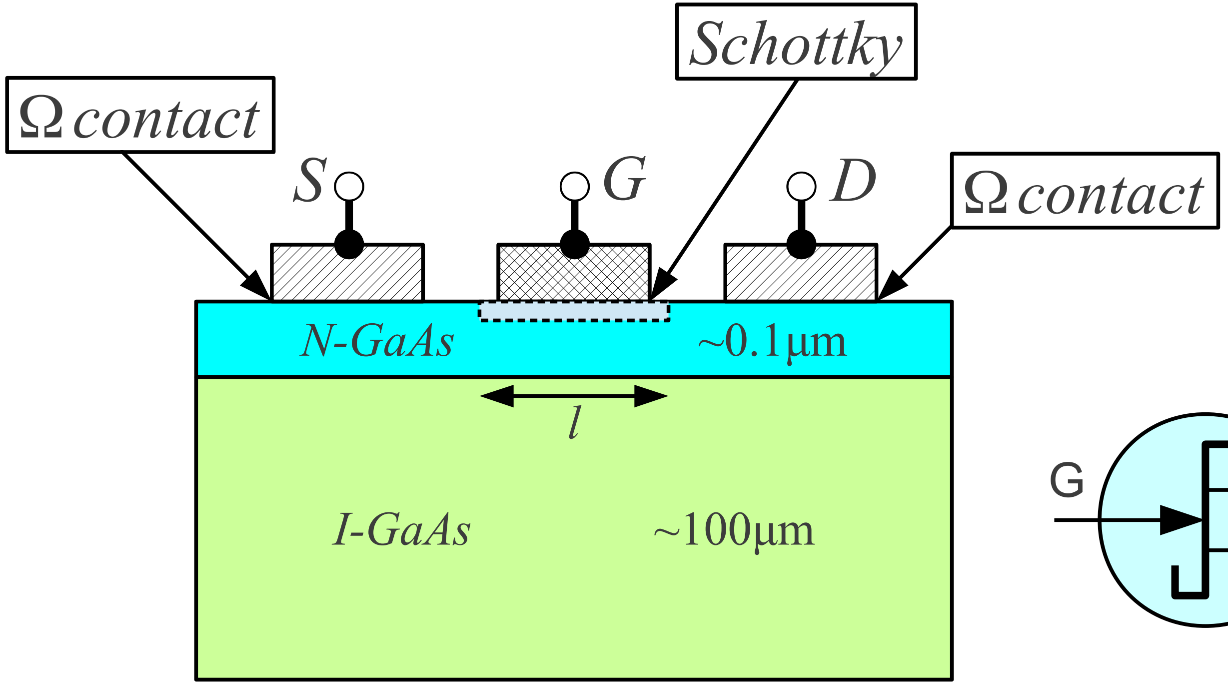


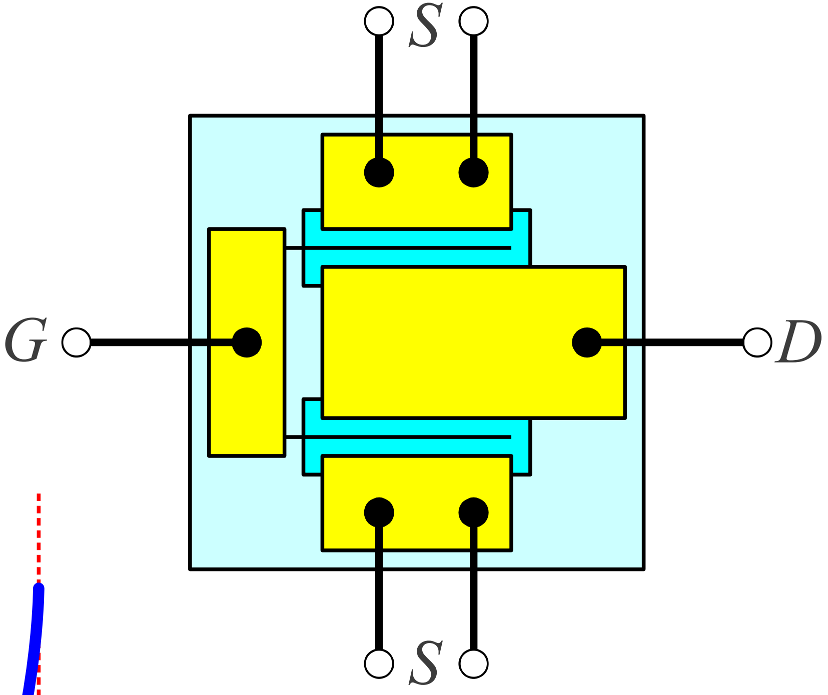
MOSFET protection diodes

$\mu_N \approx 5000 \mathrm{cm}^2/\mathrm{Vs}$

$l \leq 1 \mu m$

$f \approx 10 \mathrm{GHz} \cdot \frac{1 \mu m}{l_{channel}}$

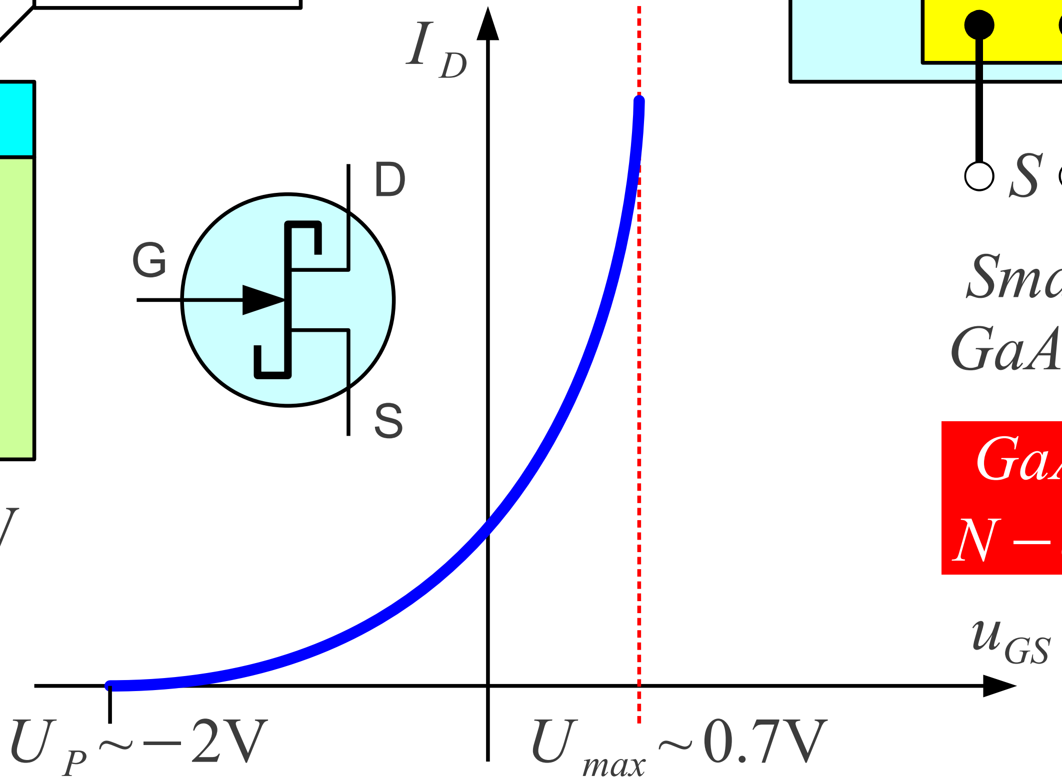




Small − signal GaAs MESFET

$U_P \approx -2\mathrm{V}$

$U_{DS} \approx 5\mathrm{V}$



GaAs: $\mu_N \gg \mu_P$
N − channel only !

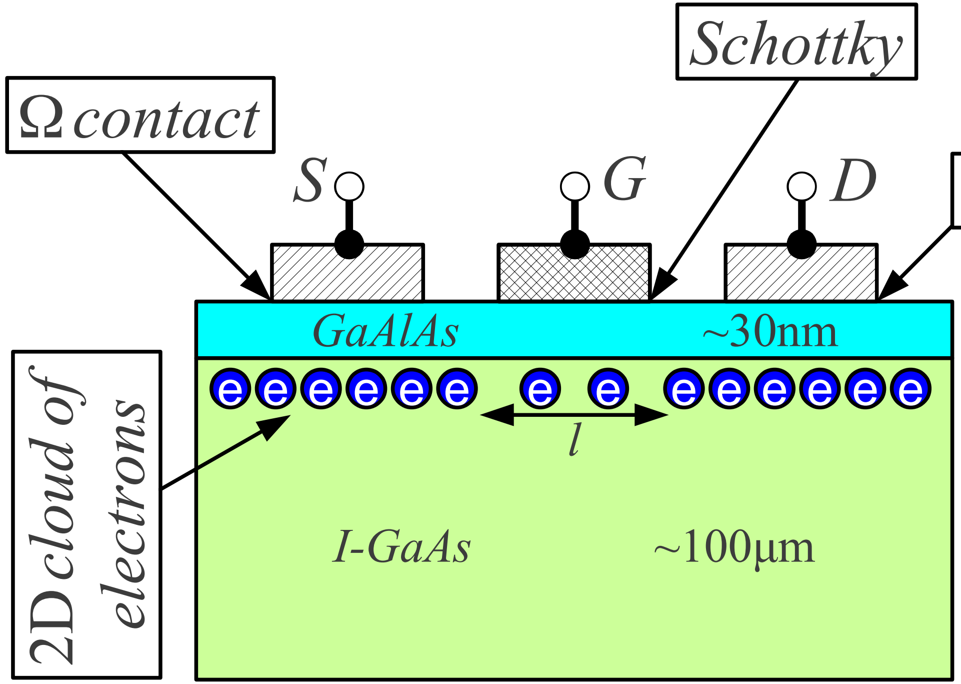
Drawings not to scale

GaAs MESFET

GaAlAs HEMT

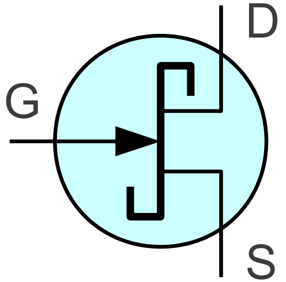
$\mu_N \approx 50000\,\mathrm{cm^2/Vs}$

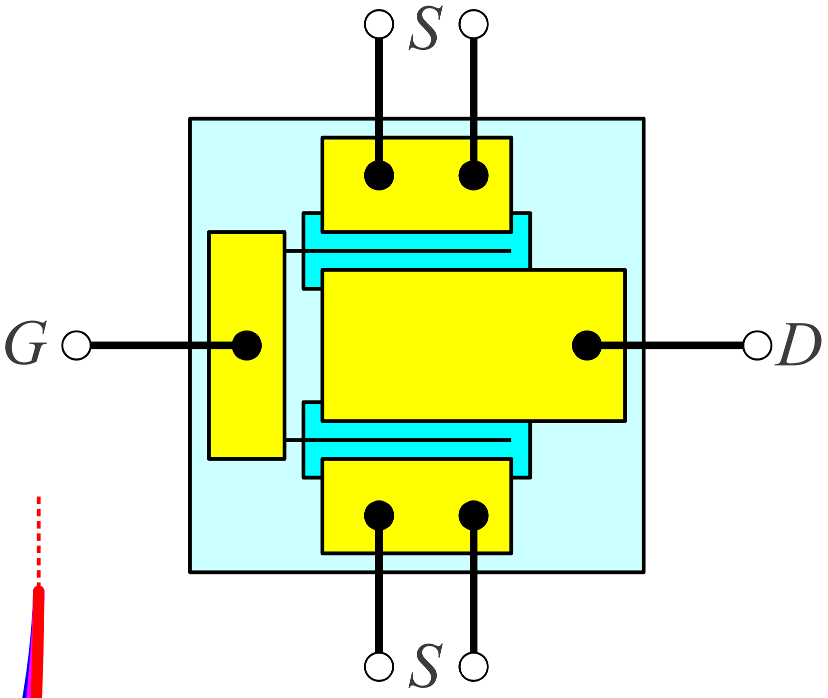
$l \leq 0.5\,\mu\mathrm{m}$



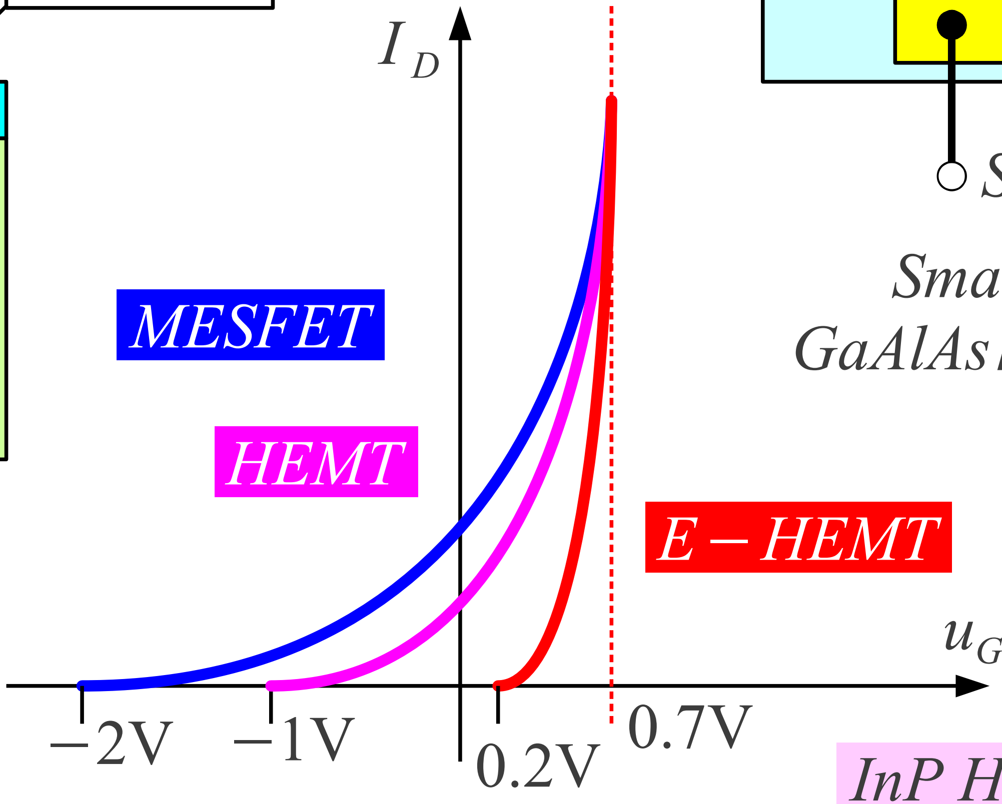
$U_P \approx -1\mathrm{V}$ $U_{DS} \approx 2\mathrm{V}$

Drawings not to scale





Small−signal GaAlAs/GaAs HEMT

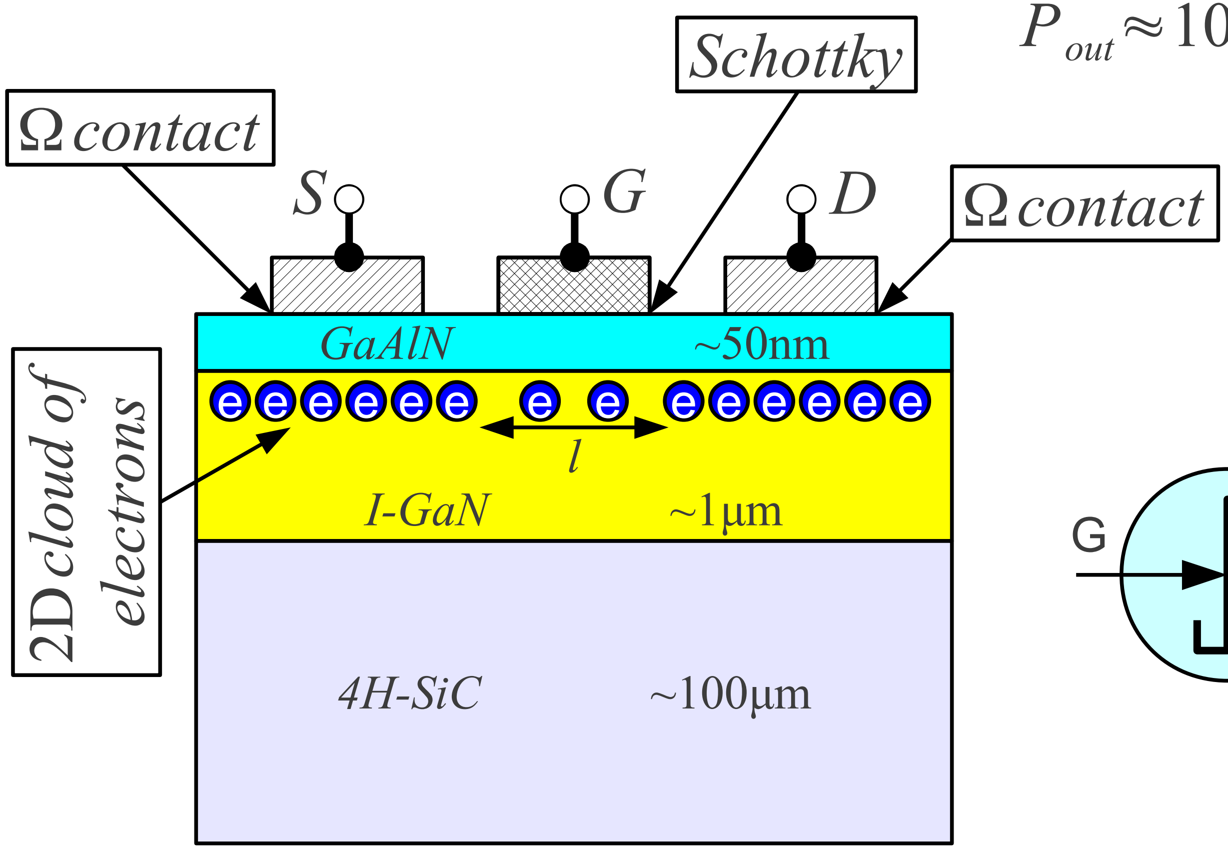


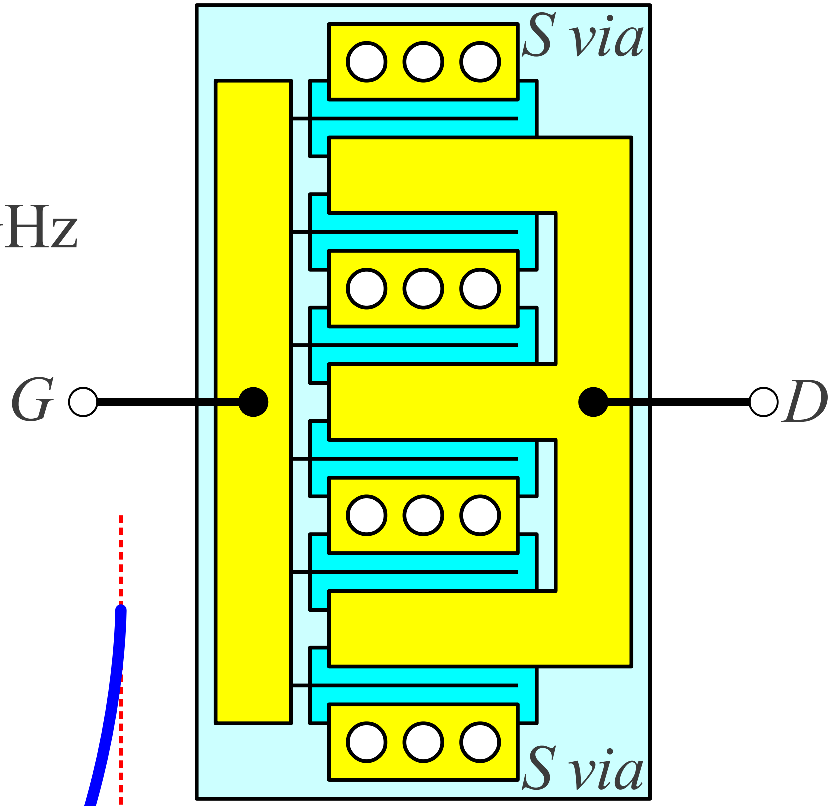
InP HEMT $f \approx 1\mathrm{THz}$

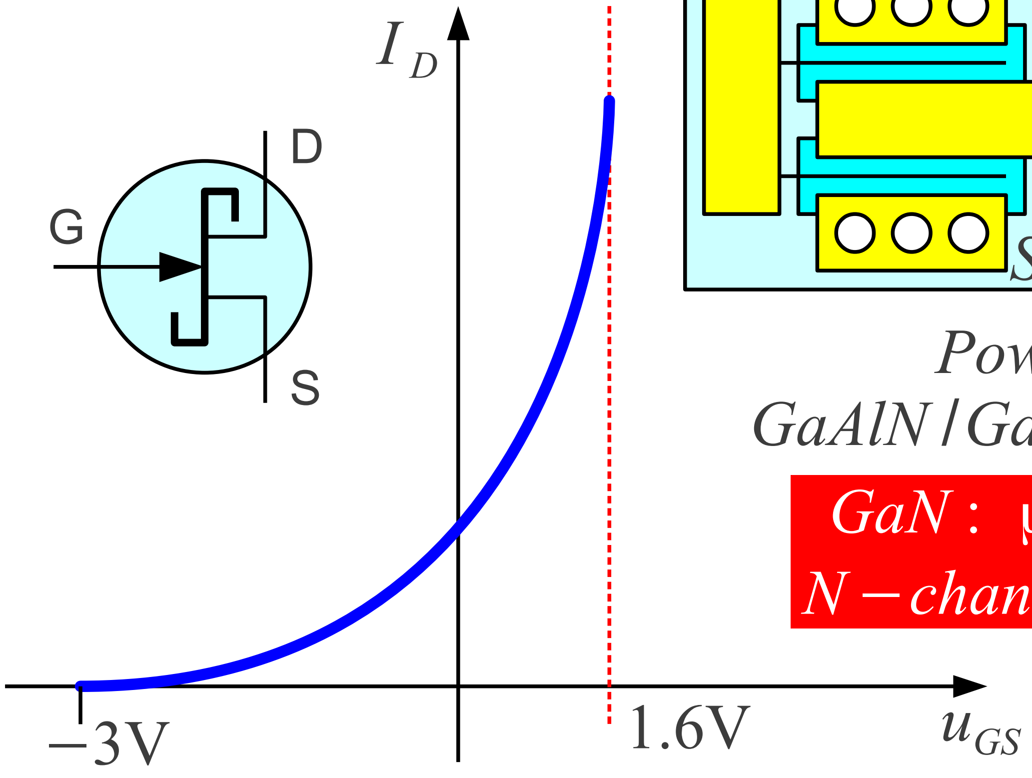
Drawings not t o scale

$l \leq 0.5\mu m$

$P_{out} \approx 100W @ 10GHz$







Power
GaAlN / GaN HEMT

$GaN: \ \mu_N \gg \mu_P$
N − channel only !

$U_P \approx -3V$

$U_{DS} \approx 50V$

GaN HEMT