Mechatronic Actuators

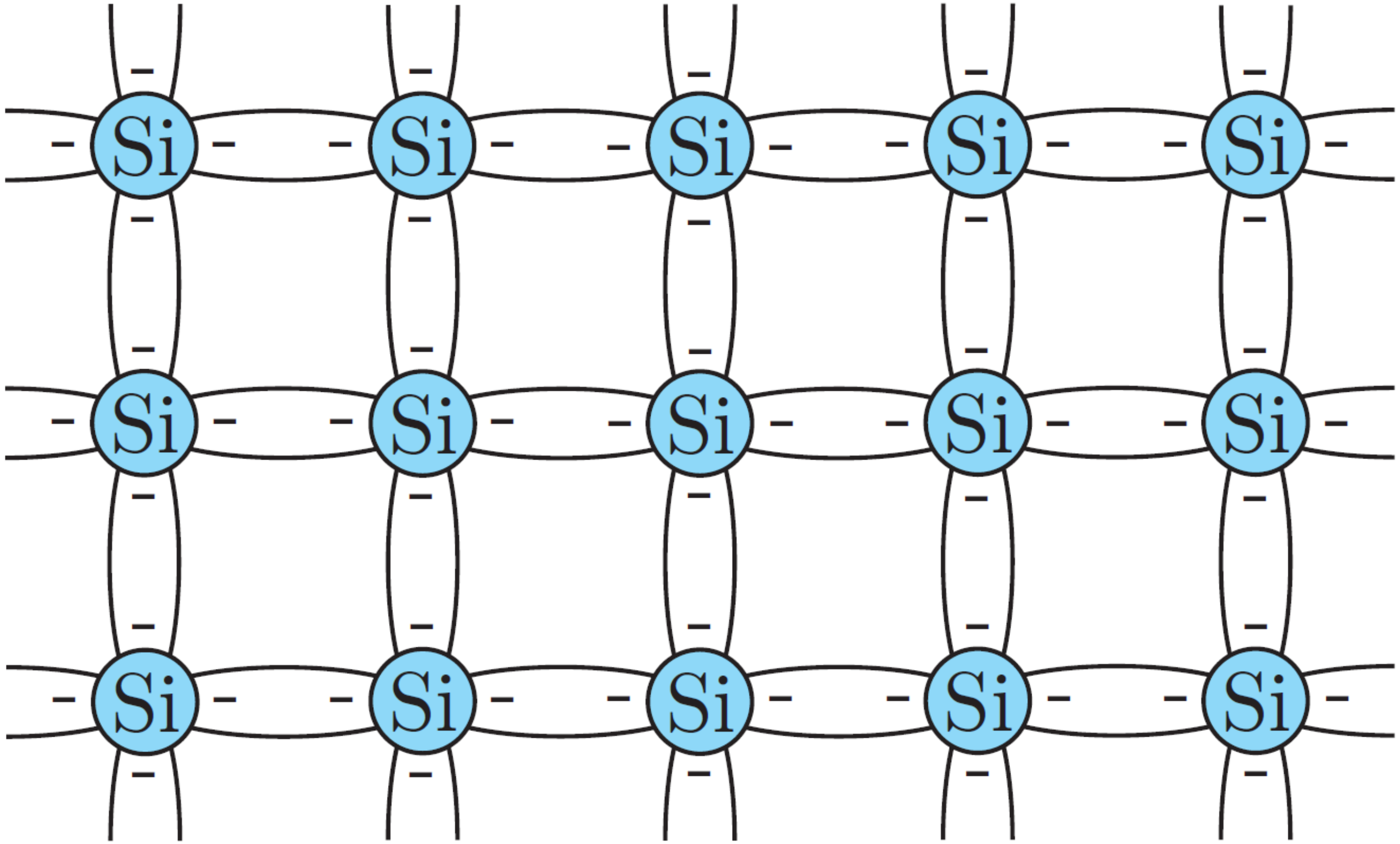
Lecture 3b

Semiconductors

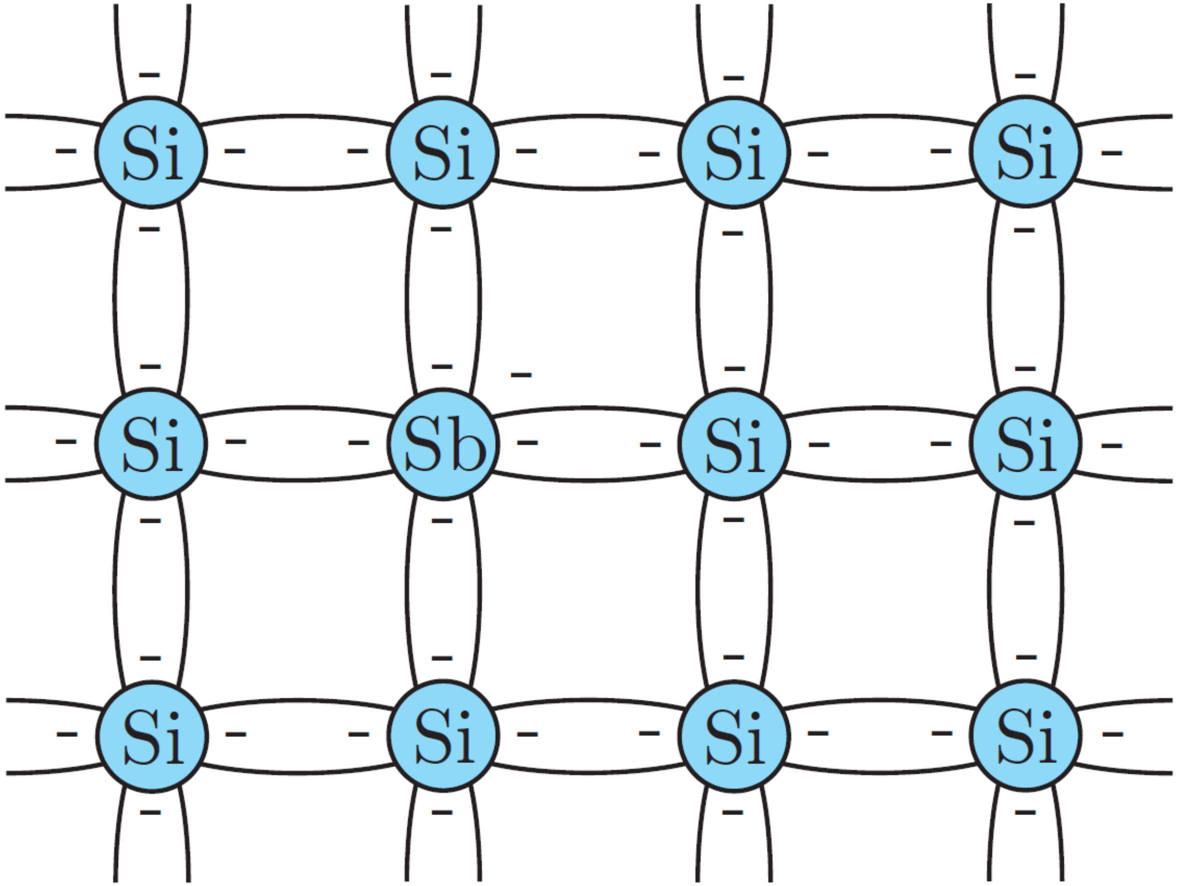
Semiconductors

- Si
- Ge
- GaAs

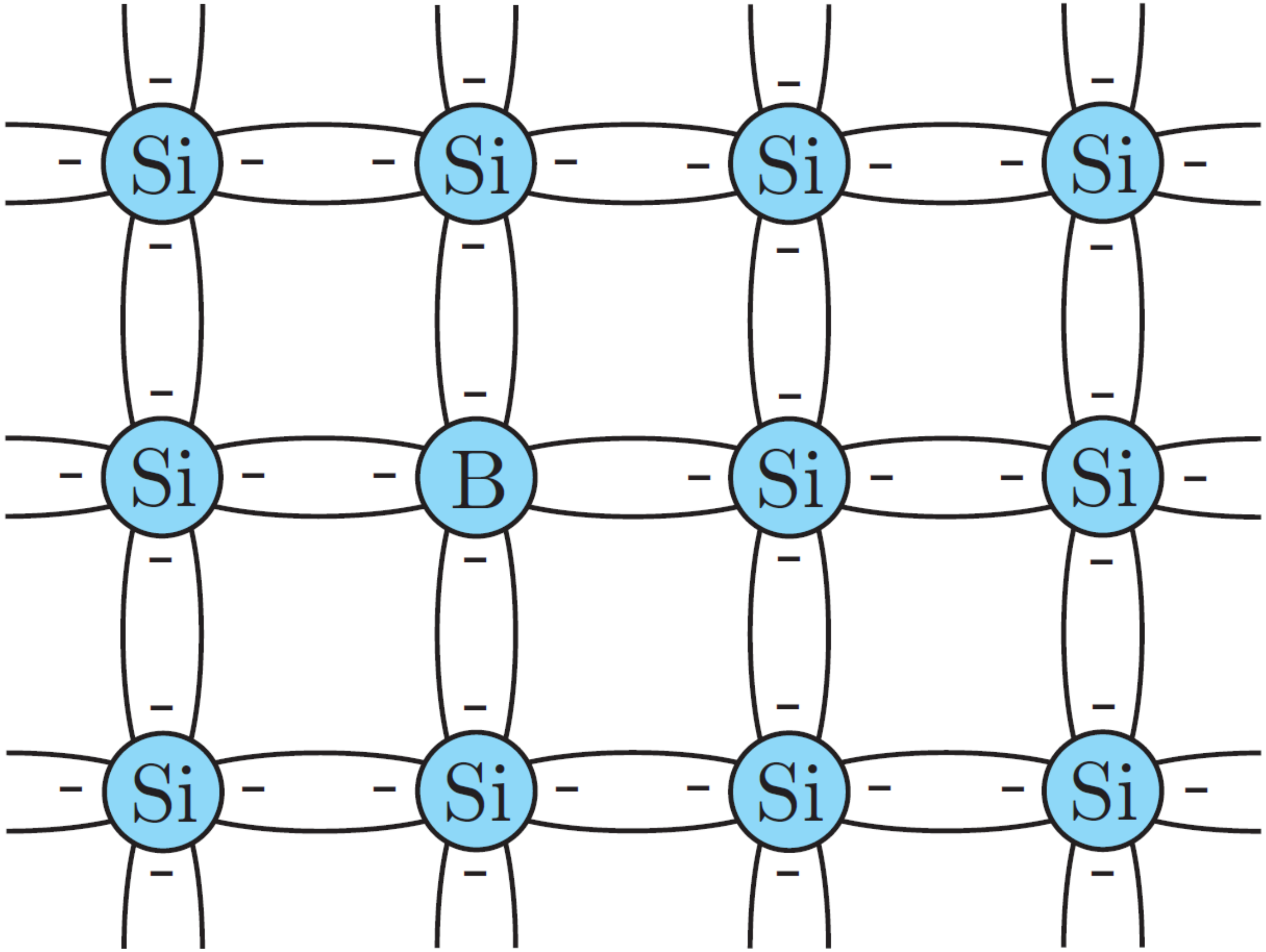
Crystal structure of silicon



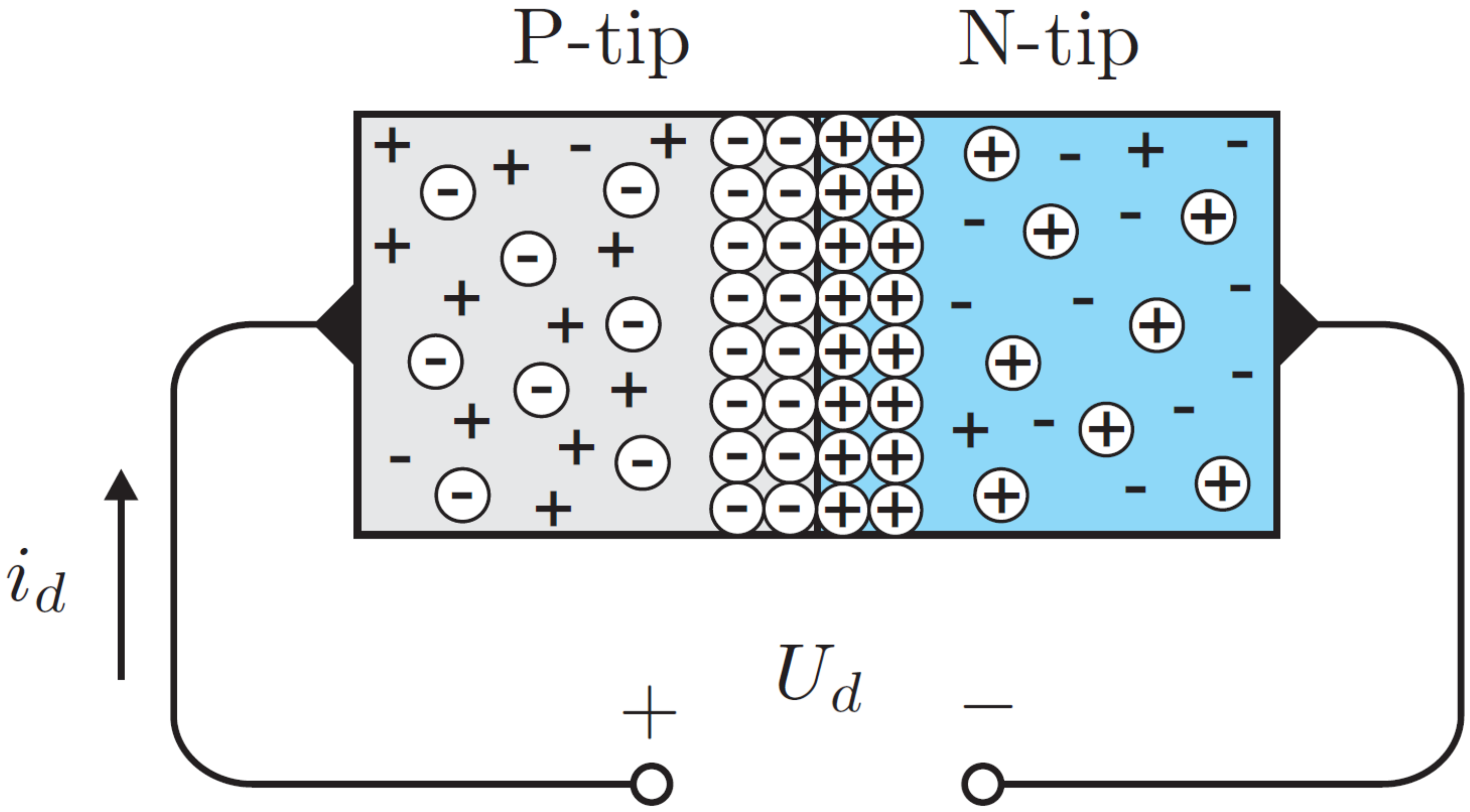
N-type semiconductor



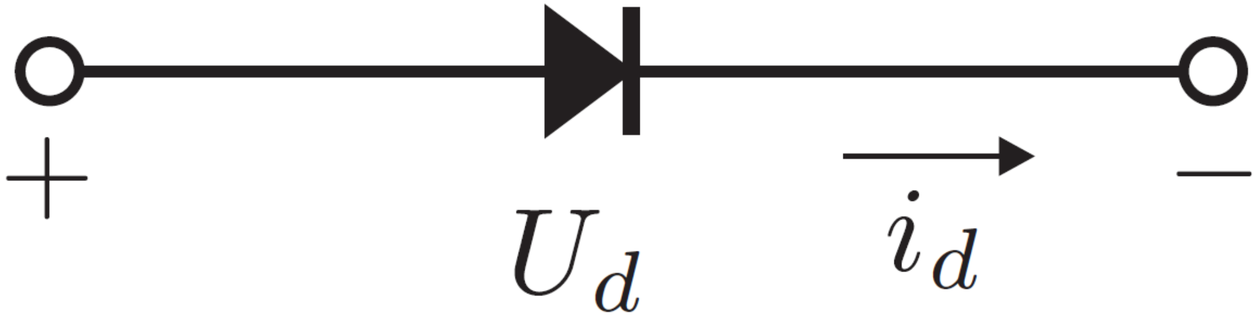
P-type semiconductor

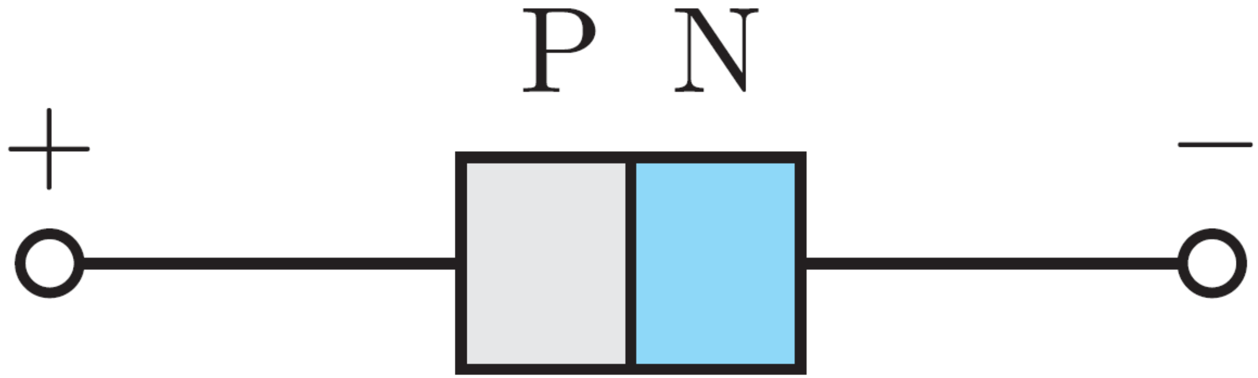


Diode

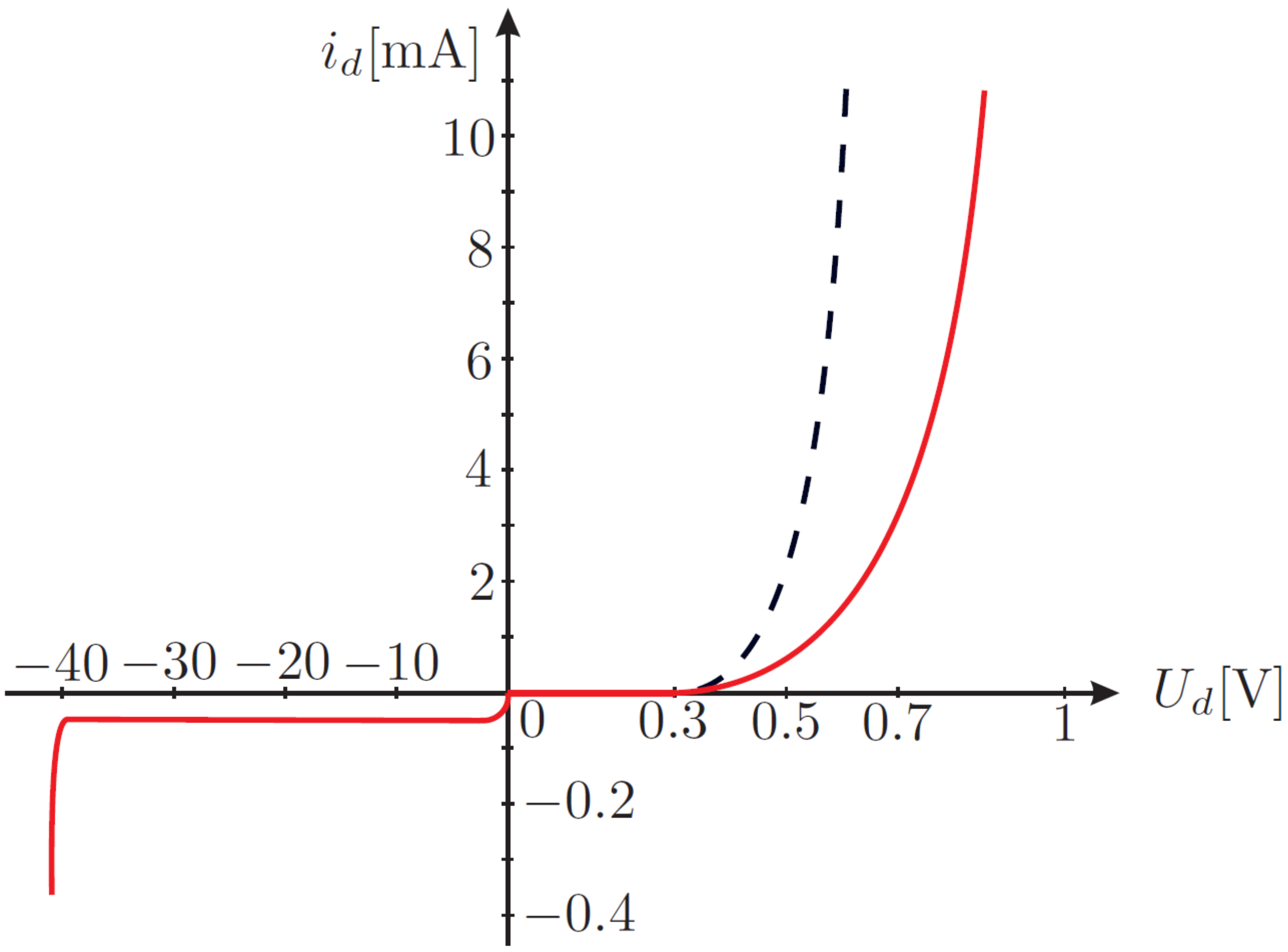


Diode (symbol)

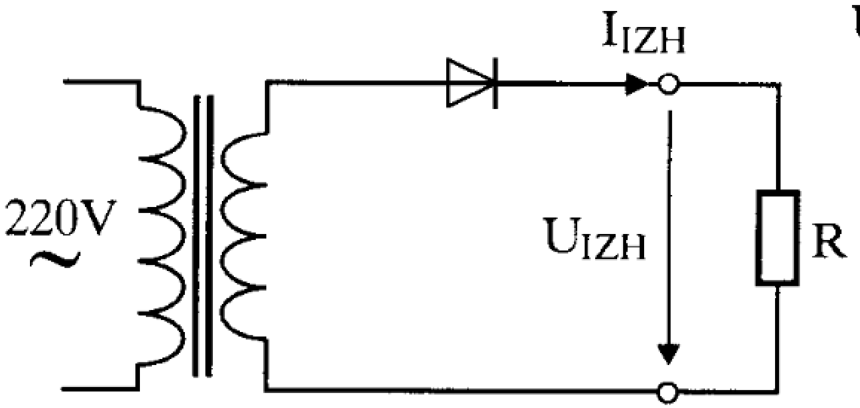


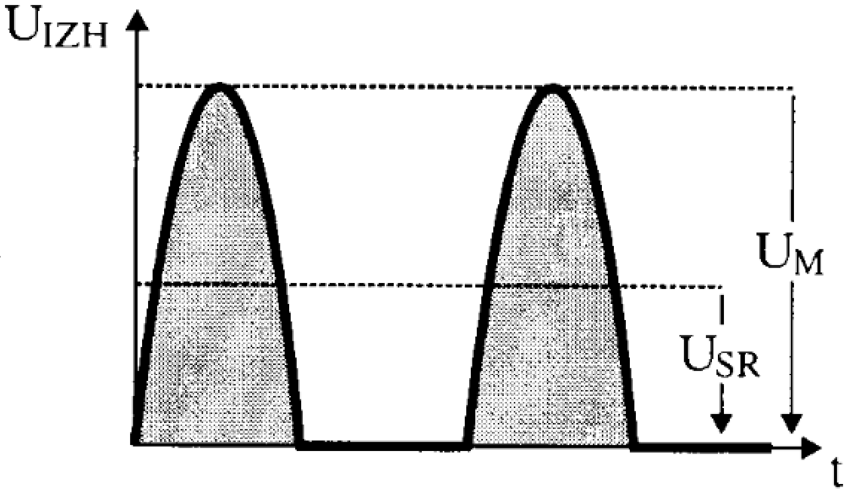


Diode characteristic

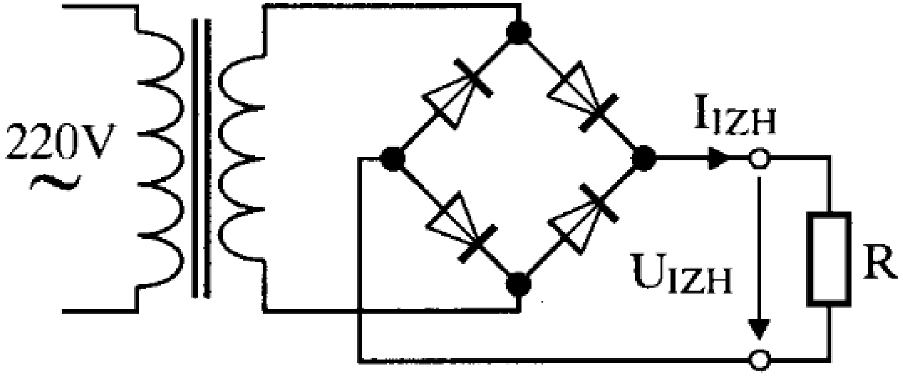


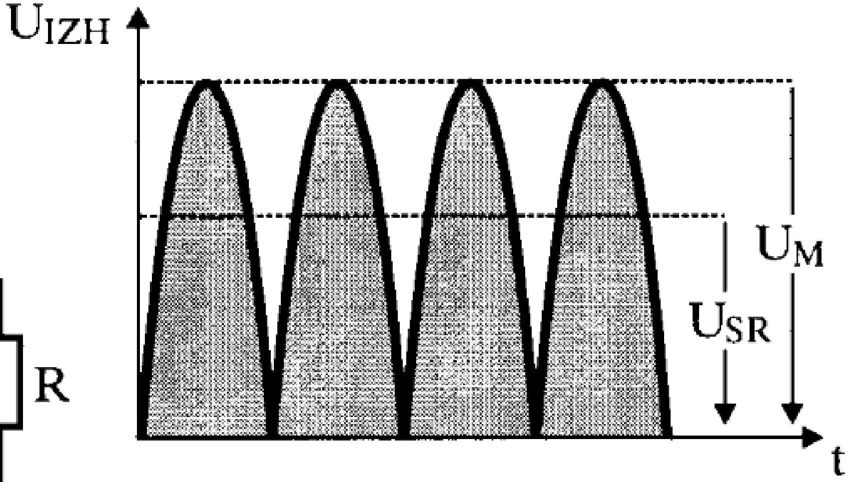
Half-wave rectifier



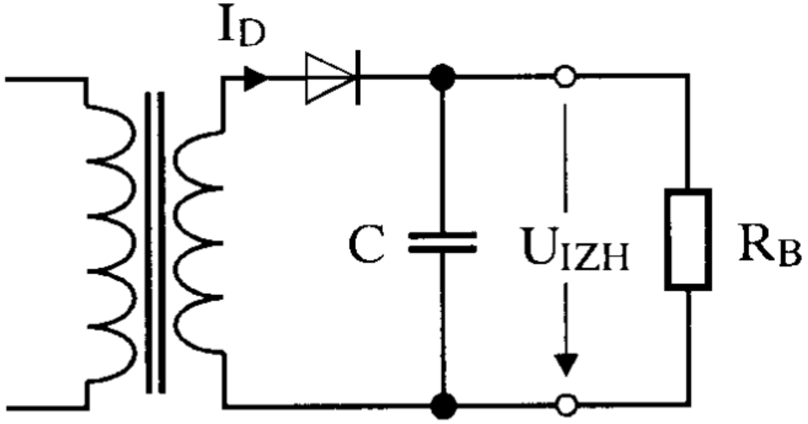


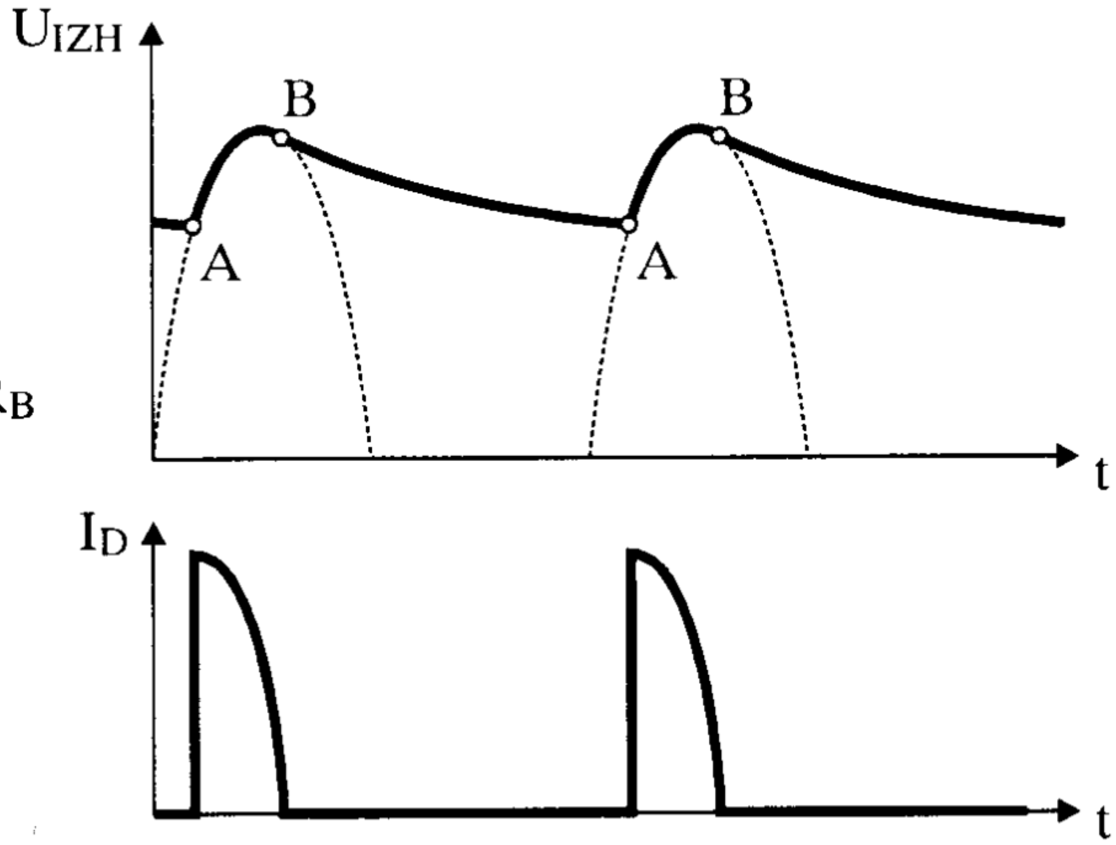
Full-wave rectifier



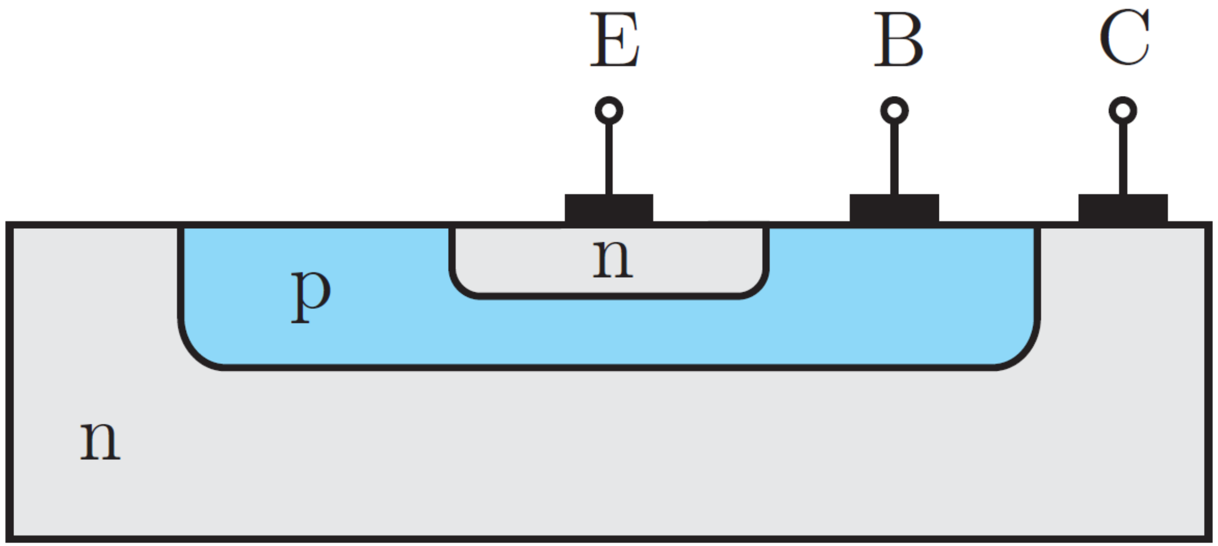


Voltage smoothing with a capacitor

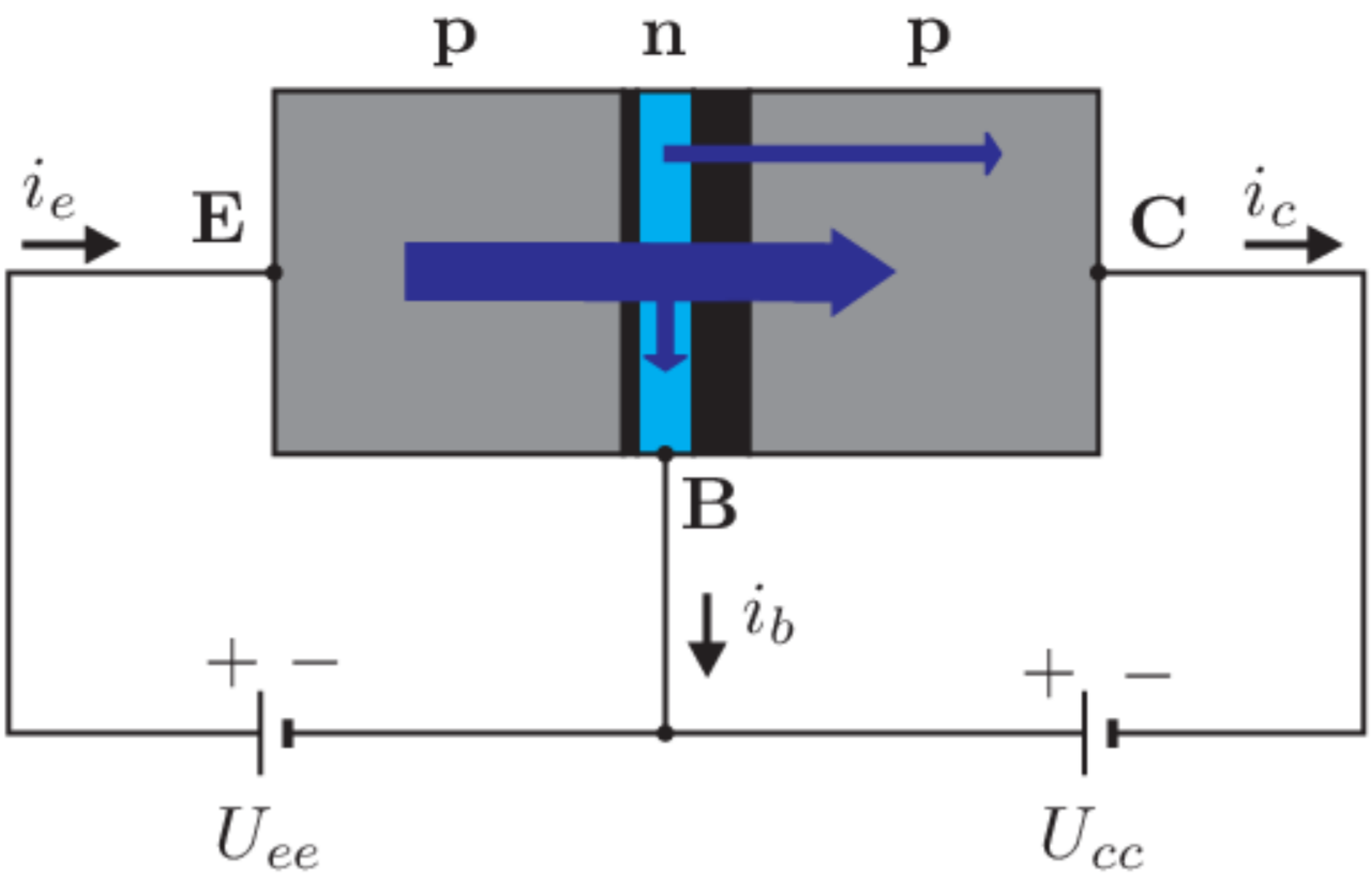




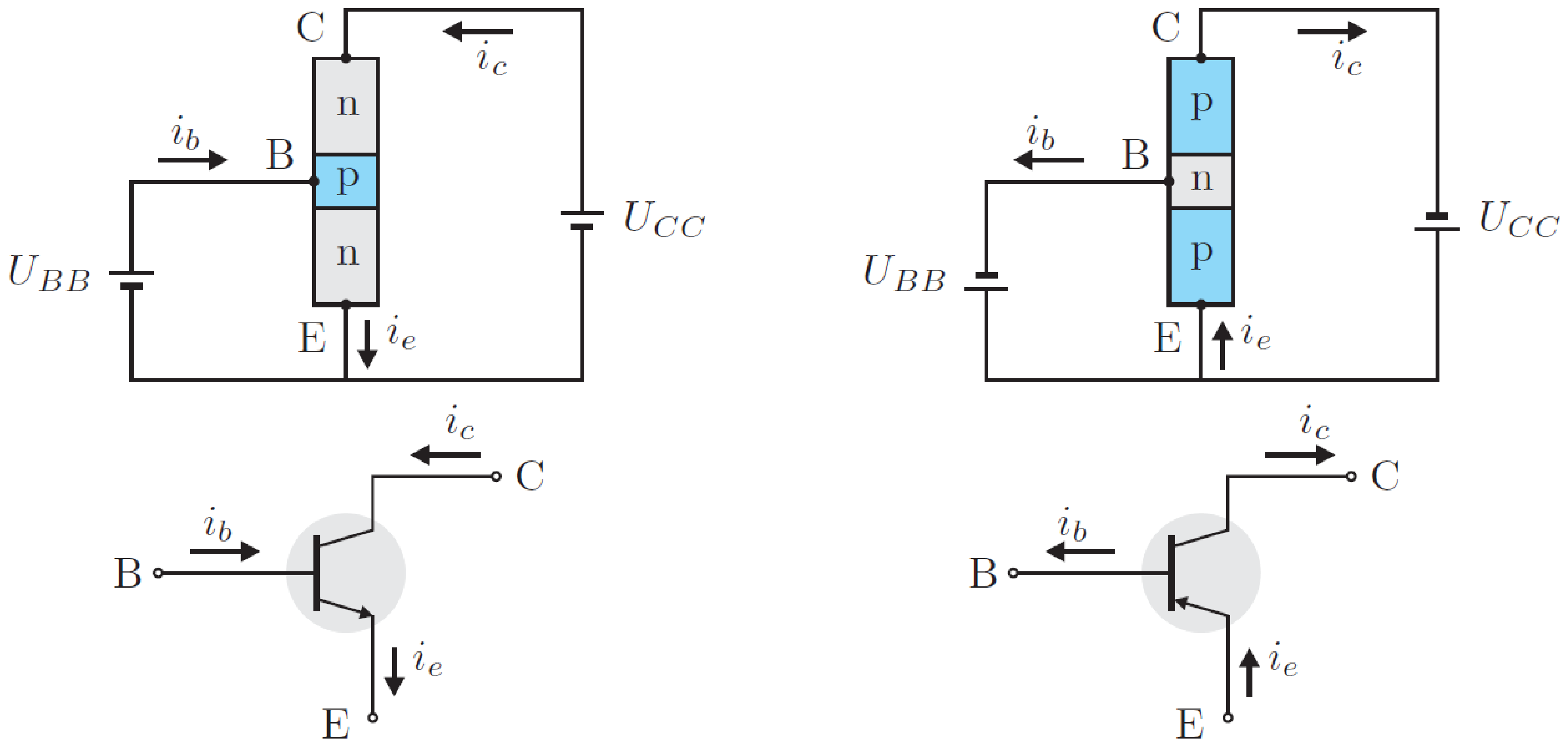
Bipolar transistor (BJT)



Principle of operation

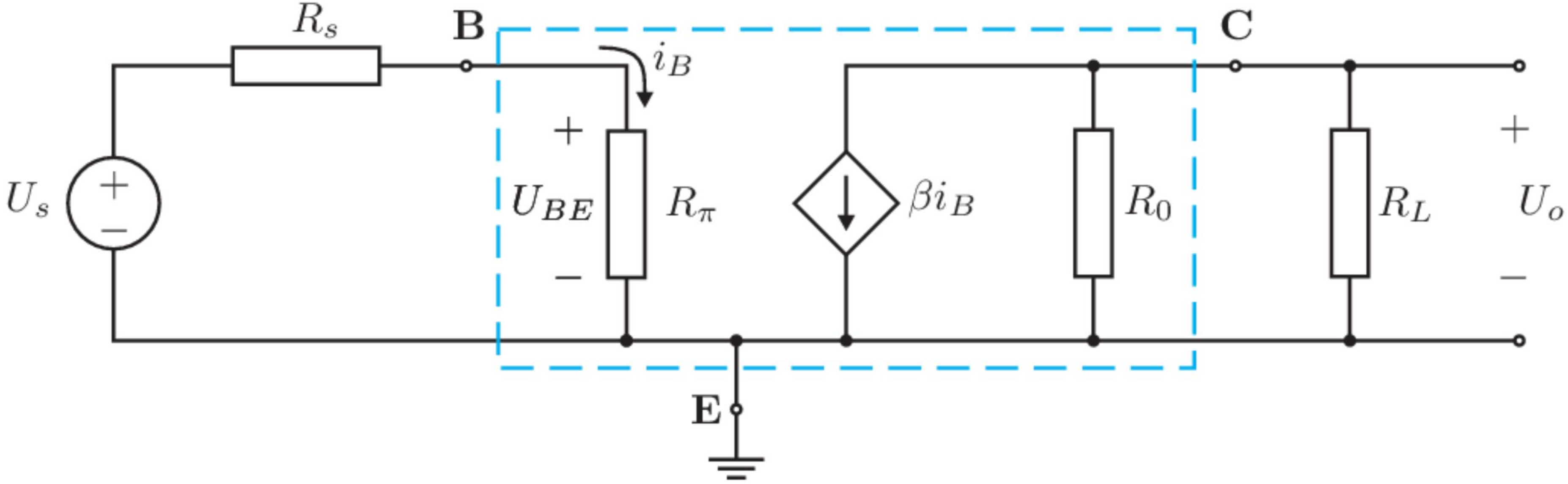


NPN and PNP orientation



$$i_e = i_b + i_c \quad ; \quad i_c = \beta i_b$$

A simplified model

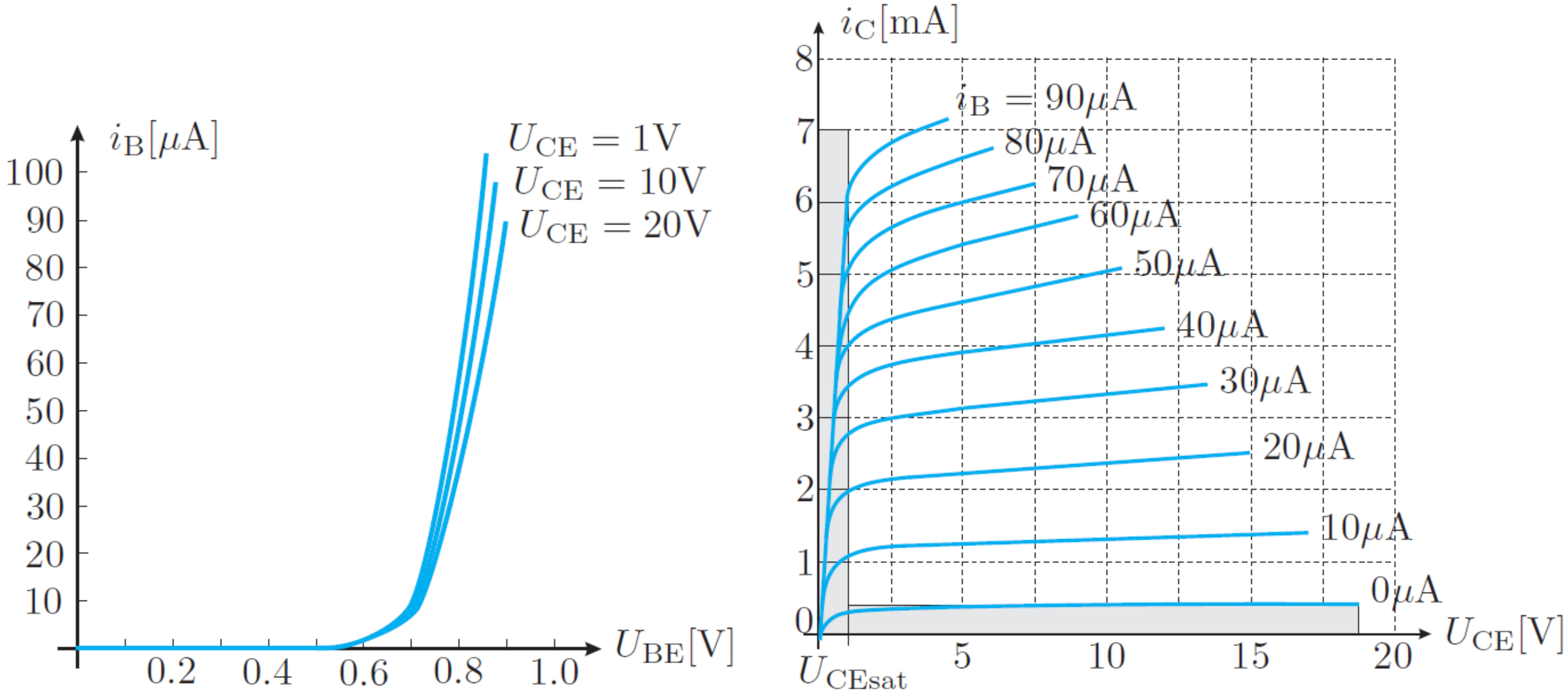


Example 1

- The transistor has a collector current of i_c=10 mA and a base current of i_b=40 µA. What is the current gain of the transistor?

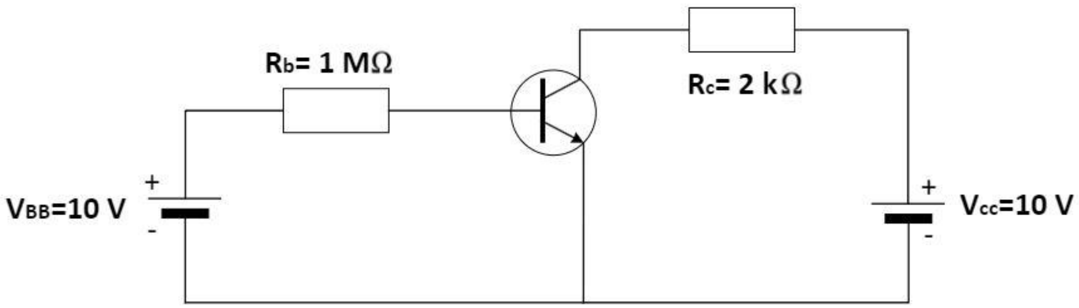
$$\beta = \frac{i_c}{i_b} = \frac{10\ mA}{40\ \mu A} = 250$$

BJT characteristic

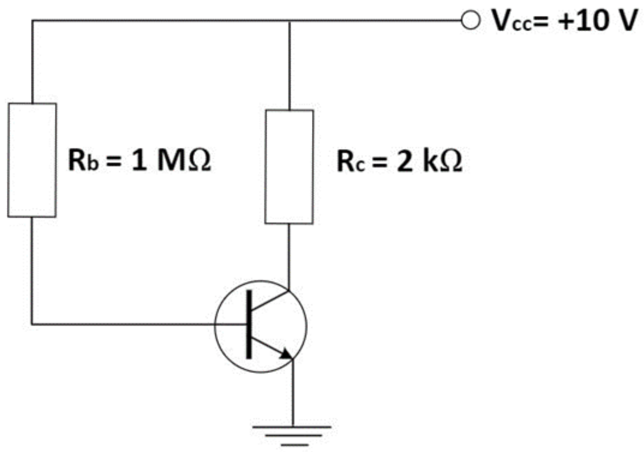


Example 2

The transistor in the figure has a current gain of β=300. Calculate i_b, i_c and P_c.



The schematic is the same as if we drew:



Example 2 (continuing)

- The base current is:

$$i_b = \frac{V_{BB} - V_{CC}}{R_b} = \frac{10\ V - 0{,}7\ V}{1\ M\Omega} = 9{,}3\ \mu A$$

- The collector current is:

$$i_c = \beta \cdot i_b = 300 \cdot 9{,}3\ \mu A = 2{,}79\ mA$$

- The voltage between collector and emitter is:

$$V_{CE} = V_{CC} - R_C \cdot i_C = 10\ V - 2\ k\Omega \cdot 2{,}79\ mA = 4{,}42\ V$$

- Power on the transistor (heating):

$$P_C = V_{CE} \cdot i_C = 4{,}42\ V \cdot 2{,}79\ mA = 12{,}3\ mW$$

Example 3

- The 2N3904 transistor operates at $V_{CE} = 10\ V$ and $i_C = 20\ mA$. Does it work in the safe area if the maximum power is 625 mW and "derating" is 5mW/°C? Do the calculation at 25°C and at 100°C.

$$P_D = V_{CE} \cdot i_C = 10\ V \cdot 20\ mA = 200\ mW$$

a.) At 25°C the power is below 625 mW.

b.) At 100°C the following applies:

$$\Delta \mathrm{T} = 100°\mathrm{C}\ - 25°\mathrm{C} = 75°\mathrm{C}$$

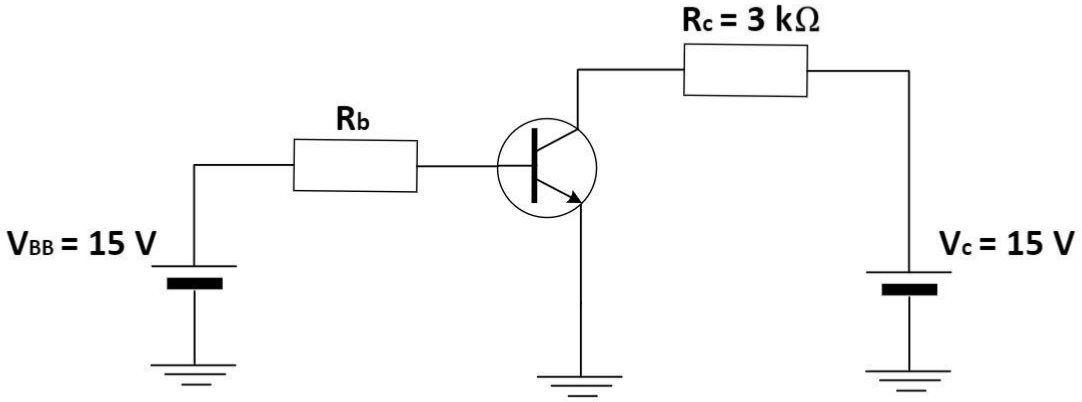
$$\Delta \mathrm{P} = \frac{5\mathrm{mW}}{°\mathrm{C}} \cdot 75°\mathrm{C} = 375\ \mathrm{mW}$$

$$P_{Dmax} = 625\ \mathrm{mW} - 375\ \mathrm{mW} = 250\ \mathrm{mW}$$

In both cases, therefore, operation is possible. A safety factor of 2 is usually taken into account. In this case, it would already be problematic at 100°C.

Example 4

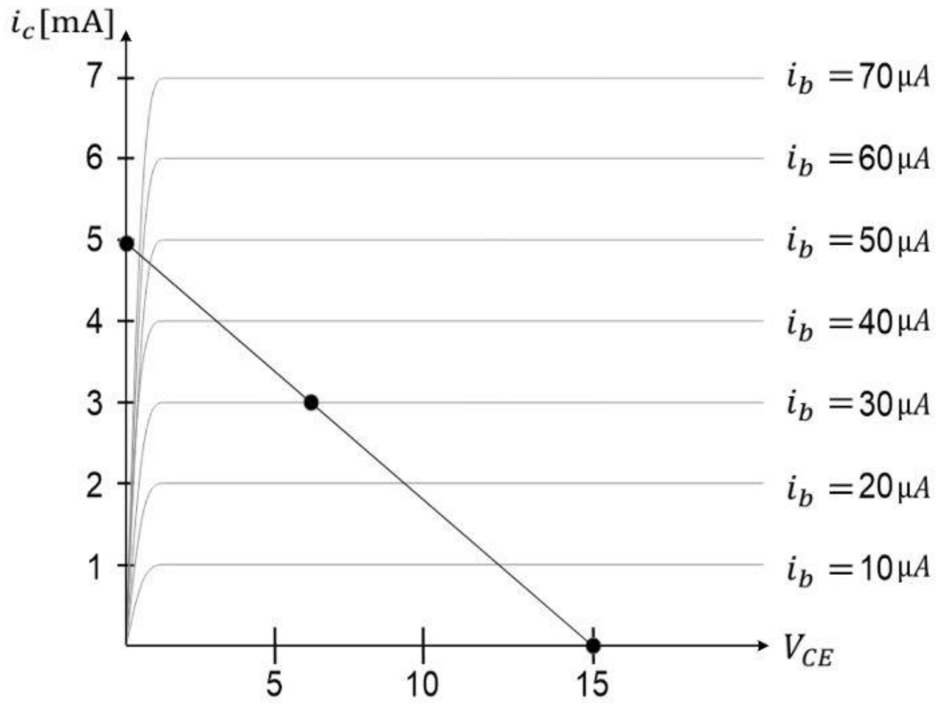
- What should the resistance $\mathrm{R_b}$ be, if we want the resistance $\mathrm{R_c} = 3\ k\Omega$ to have the power of 27 mW?



$$\mathrm{P_c} = \mathrm{R_c} \cdot i_\mathrm{c}^2 \ \Rightarrow \ i_c = \sqrt{\frac{P_c}{R_C}} = 3\ mA$$

Example 4 (continuing)

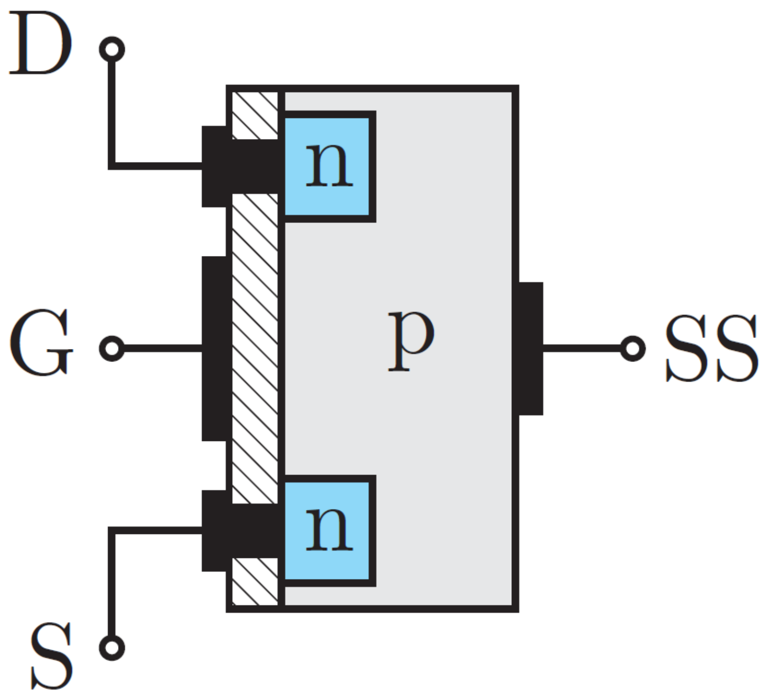
- $i_c = \frac{U_{CC}}{R_C} - \frac{U_{CE}}{R_C}$

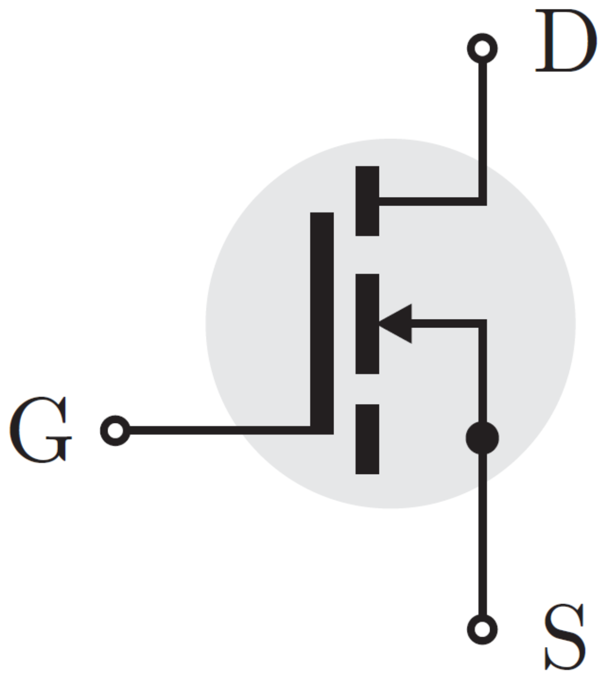


- From the graph: $i_b = 30\ \mu A$

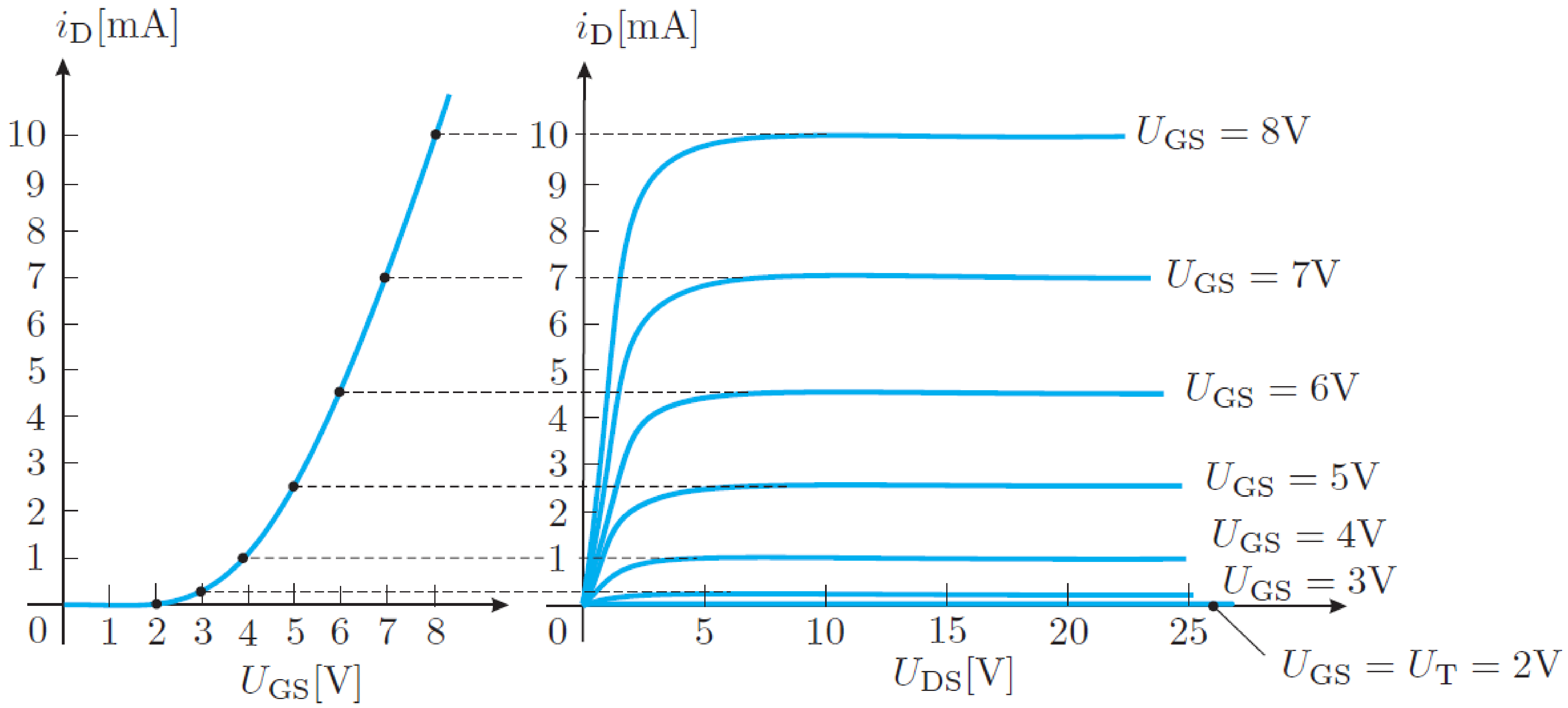
- Resistance $R_b = \frac{V_{bb}}{i_b} = \frac{15\ V}{30\ \mu A} = 500\ k\Omega$

Field-effect transistor (FET)

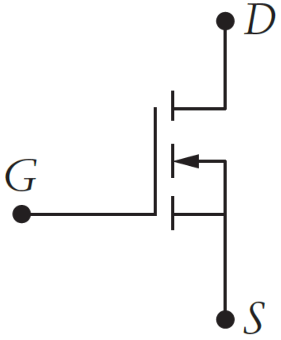




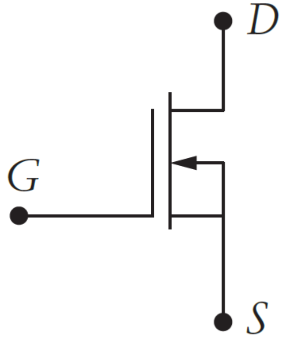
FET characteristic



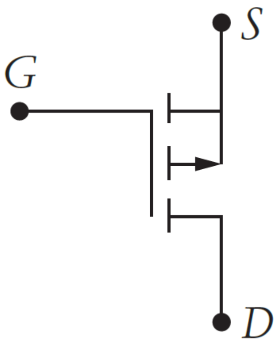
MOSFET types



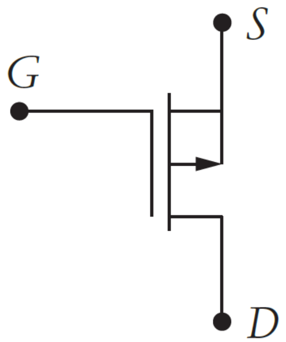
NMOS, Enhanced mode



NMOS, Depletion mode

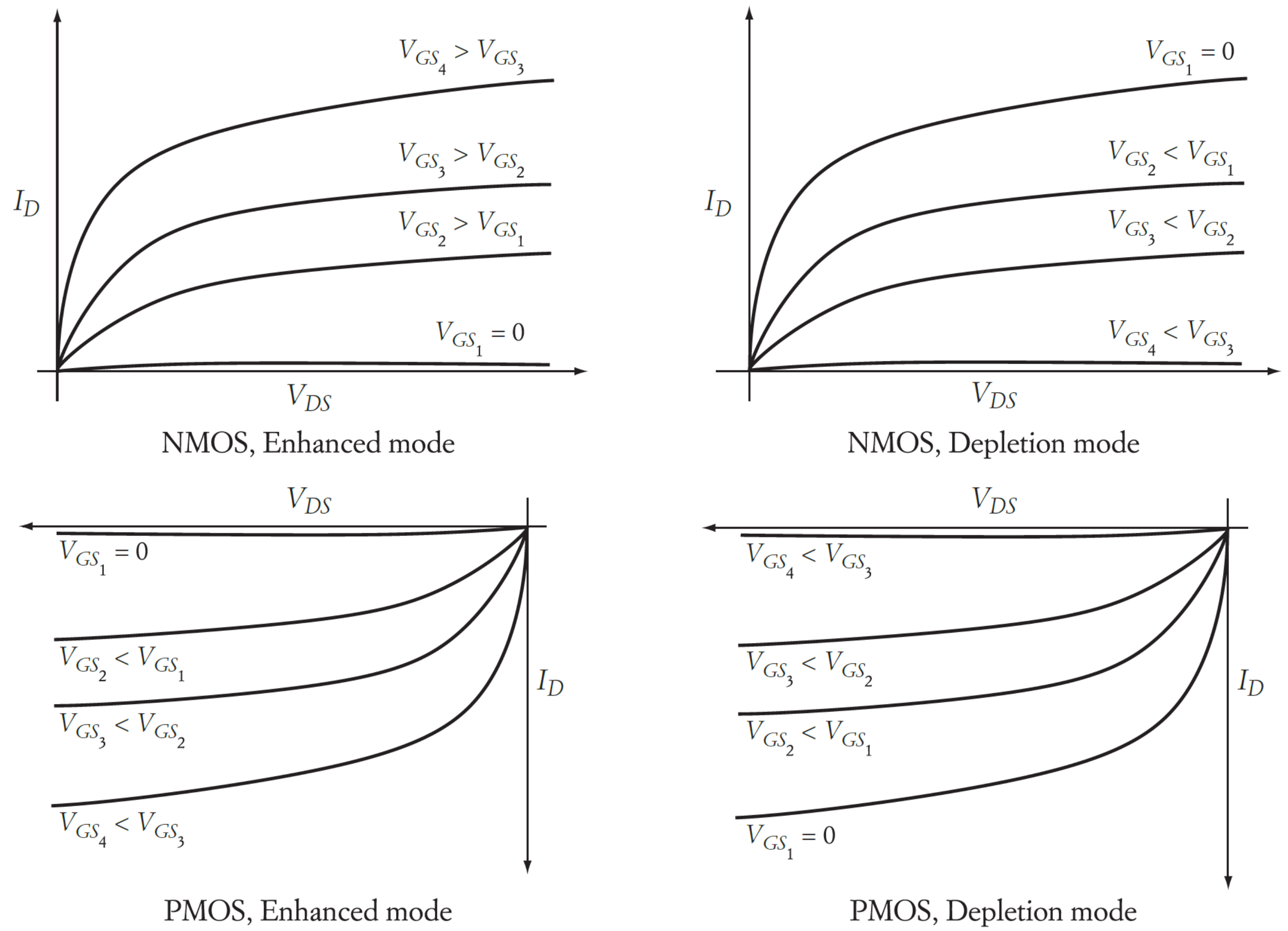


PMOS, Enhanced mode

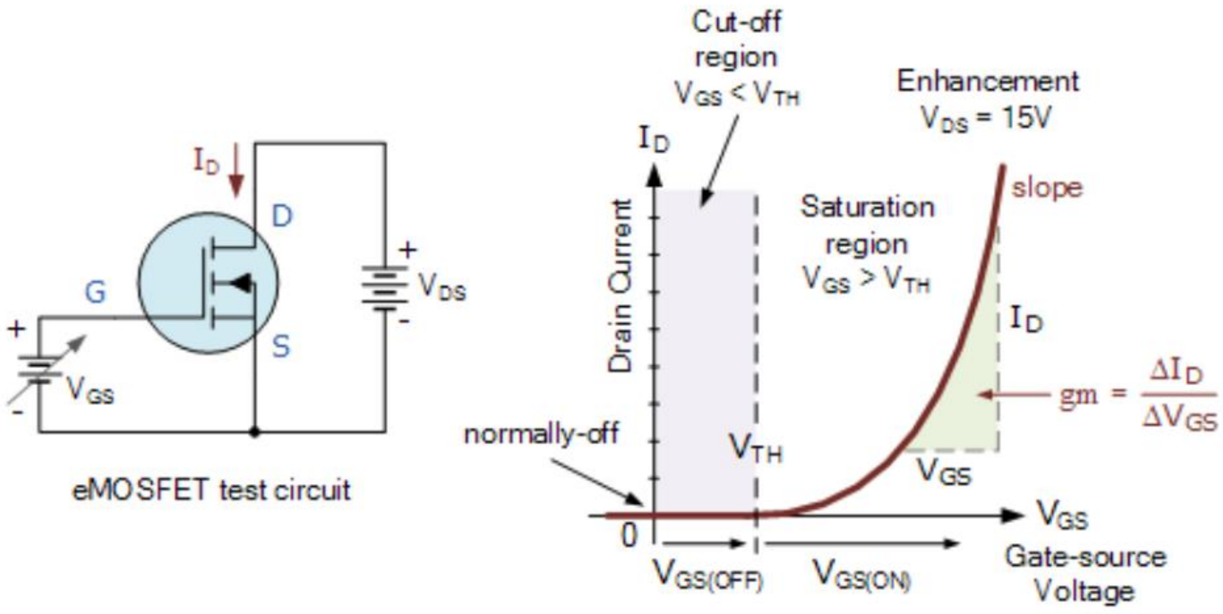


PMOS, Depletion mode

MOSFET characteristics



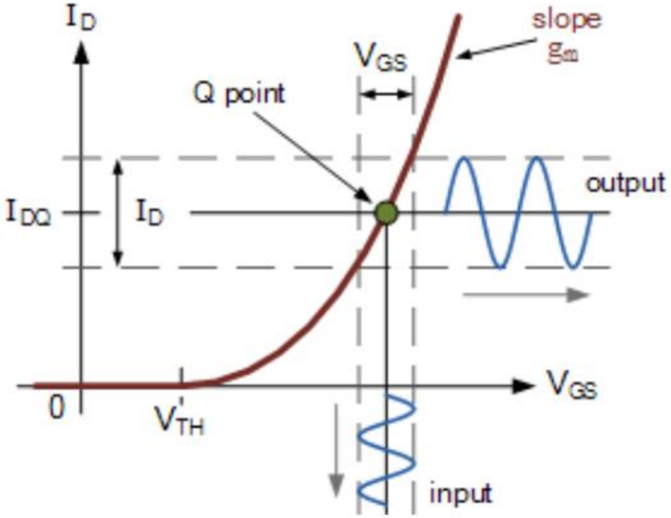
N-channel eMOSFET I-V characteristics

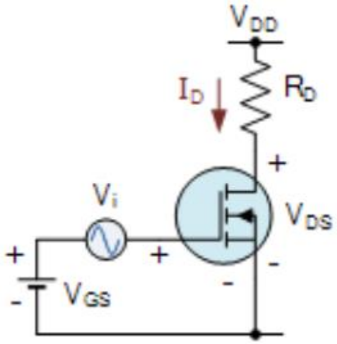


Transfer conductance (gm) $gm = \frac{\Delta I_D}{\Delta V_{GS}}$

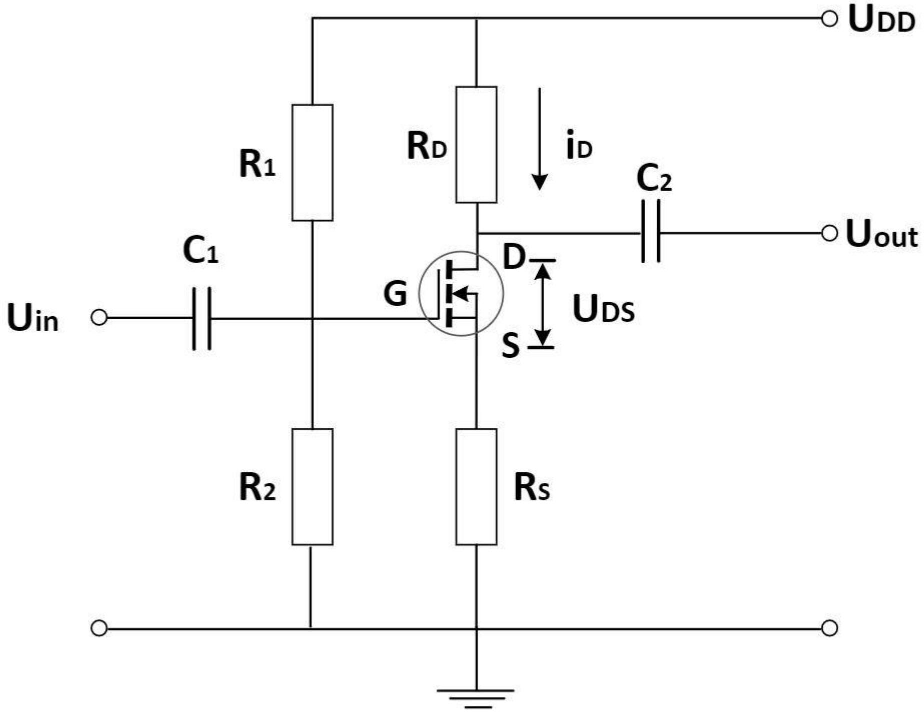
eMOSFET drain current: $I_D = k\left(V_{GS} - V_{TH}\right)^2$

eMOSFET DC bias point

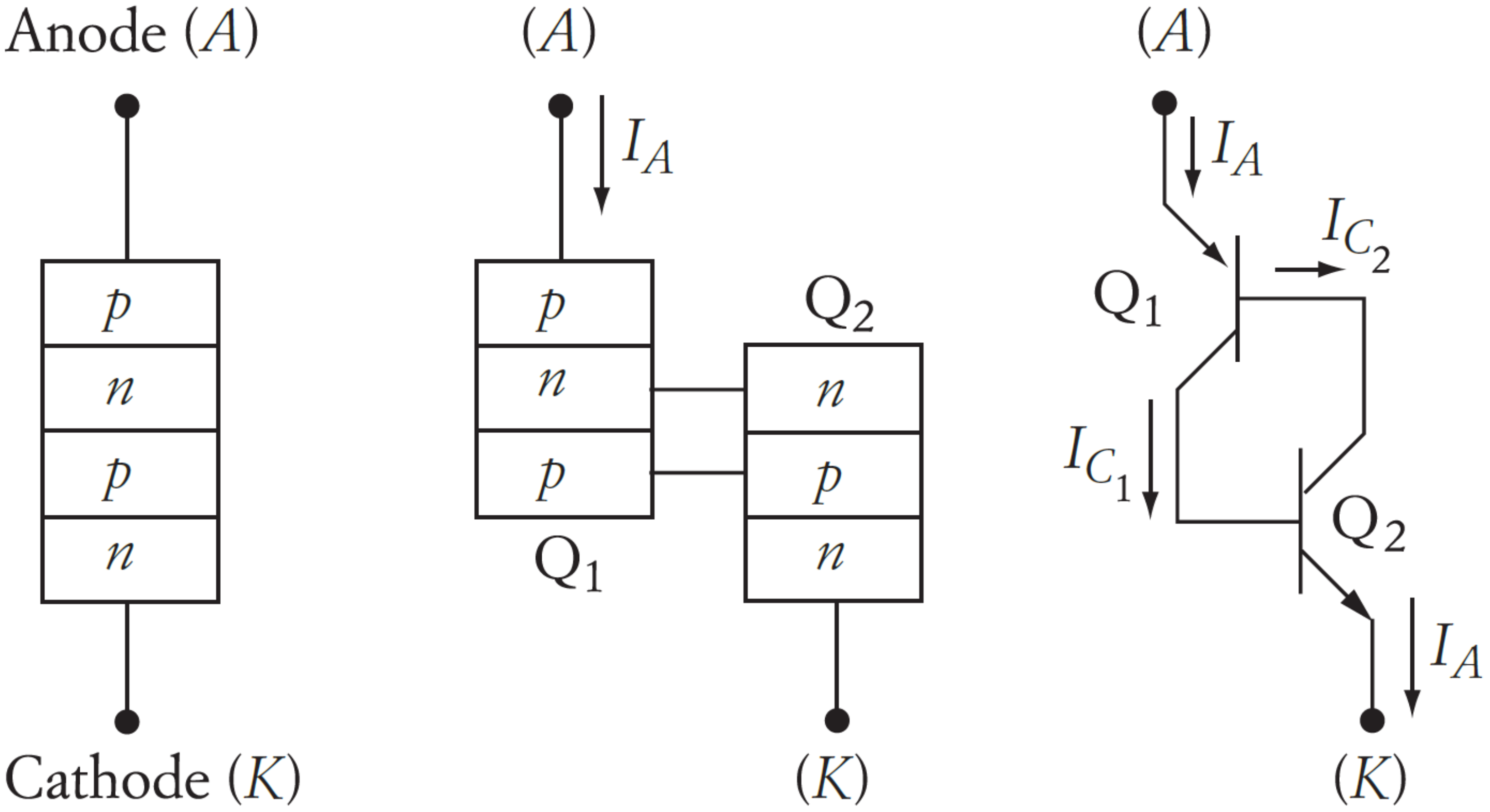




Amplifier based on MOSFET with conduction coefficient



Thyristor



Equations

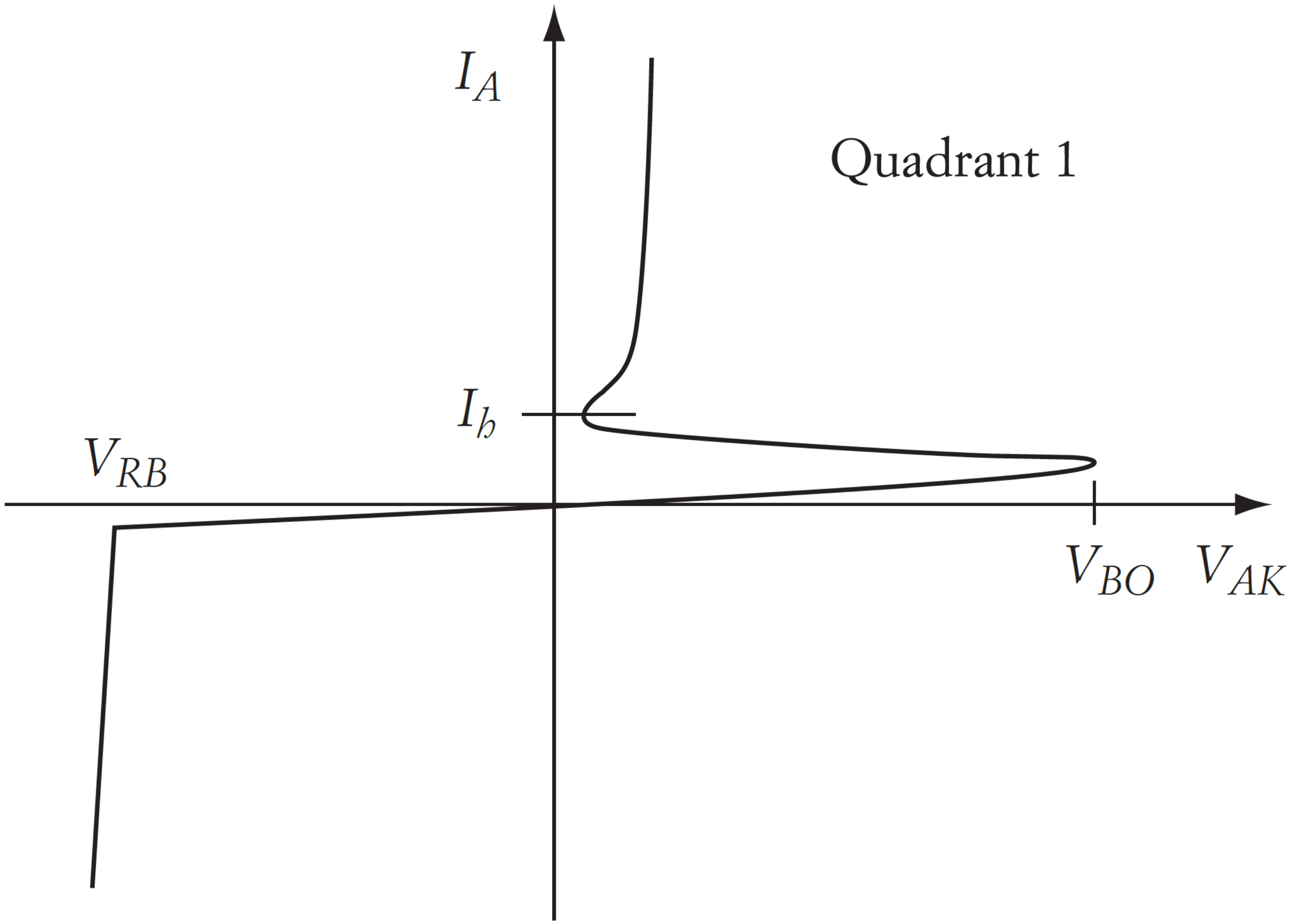
$$I_{C_1} = \alpha_1 I_A + I_{CBO_1}$$

$$I_{C_2} = \alpha_2 I_A - I_{CBO_2}$$

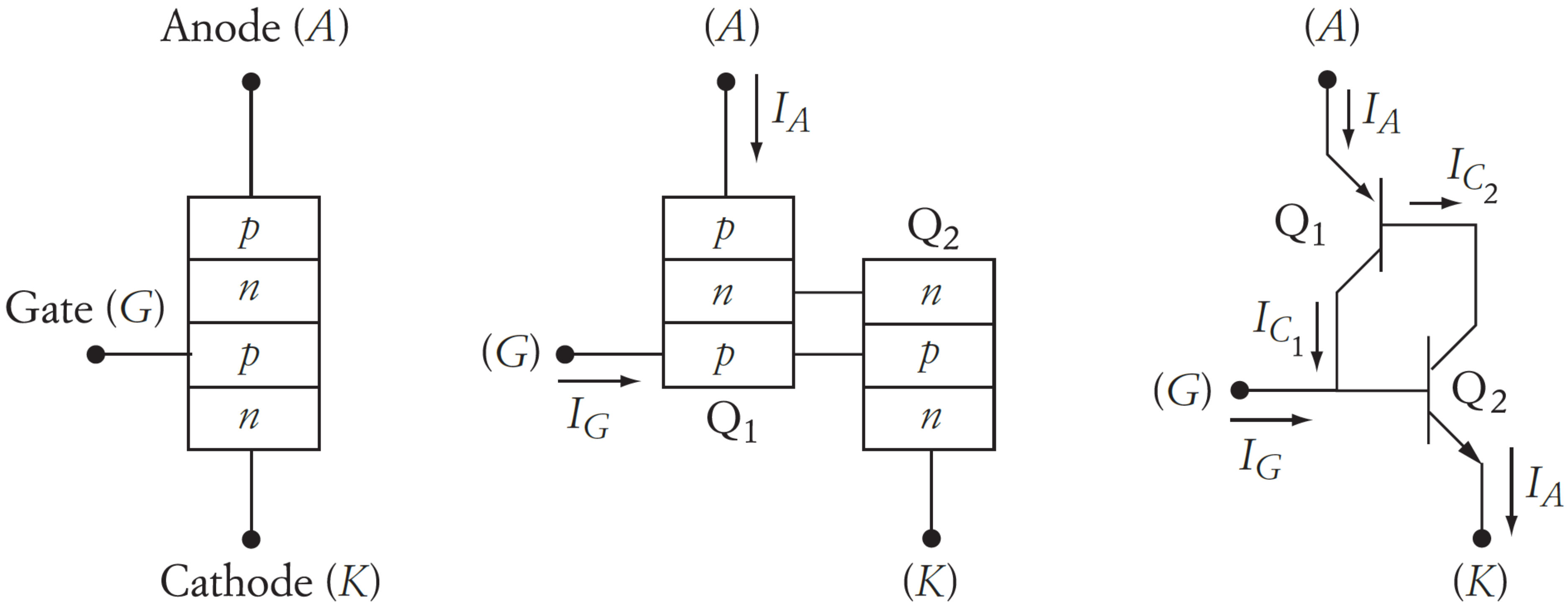
$$I_A = I_{C_1} + I_{C_2}$$

$$I_A = \frac{I_{CBO_1} - I_{CBO_2}}{1 - (\alpha_1 + \alpha_2)}$$

Thyristor characteristic

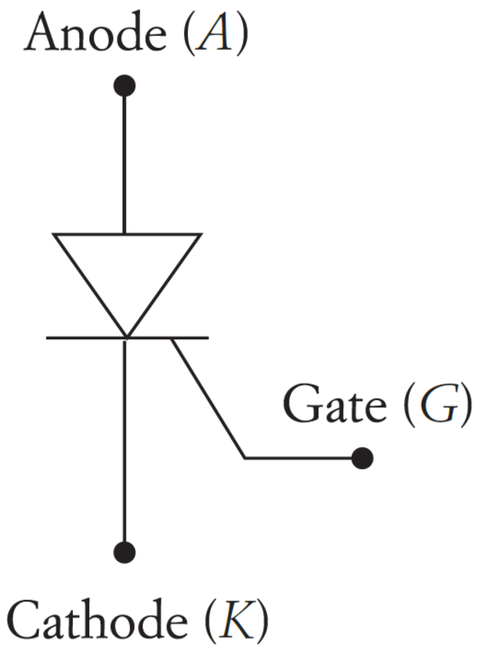


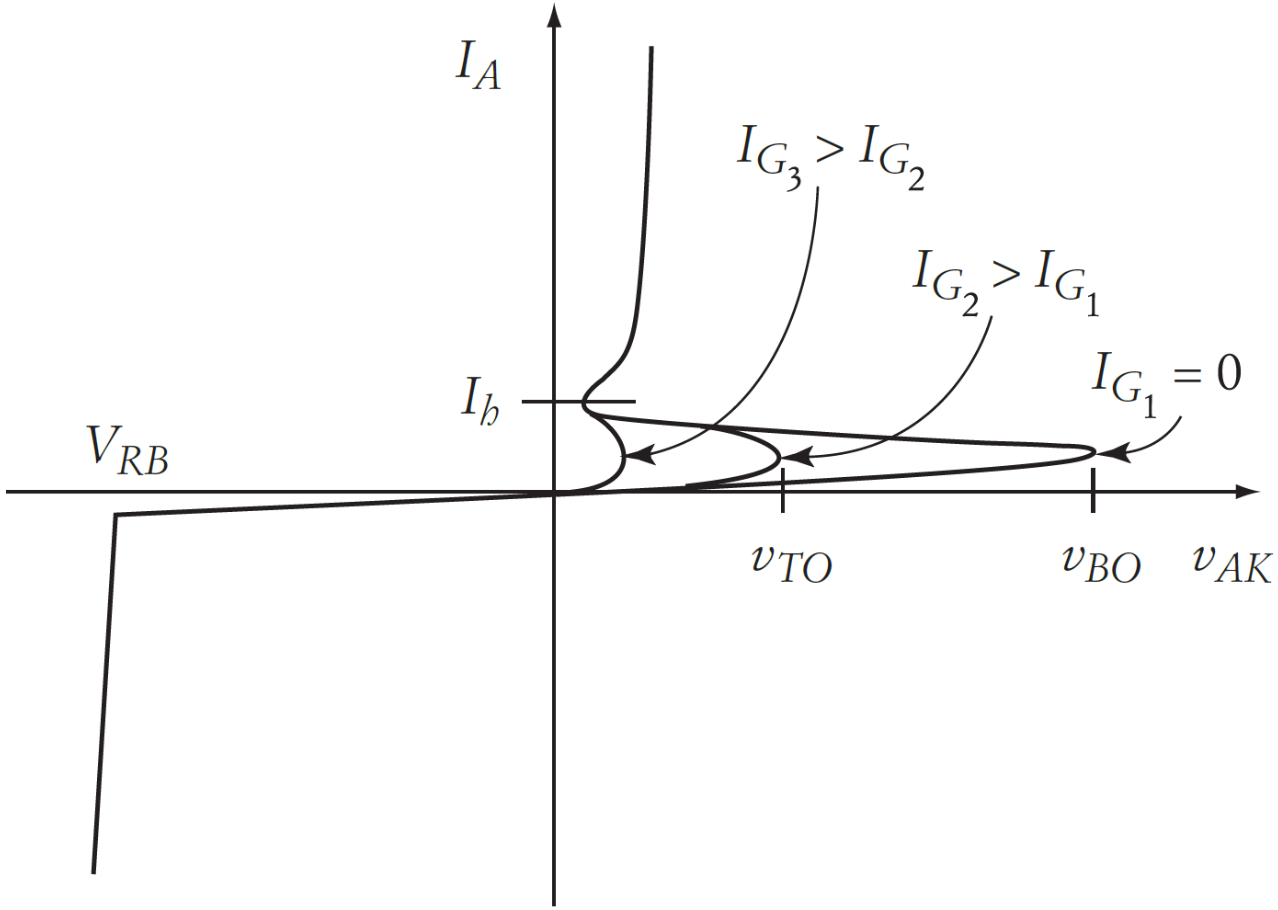
SCR



Anode (A)
Gate (G)
p
n
p
n
Cathode (K)
(A)
I_A
(G)
I_G
Q_1
Q_2
(K)
(A)
I_A
I_C2
Q_1
I_C1
(G)
I_G
Q_2
I_A
(K)

SCR characteristic

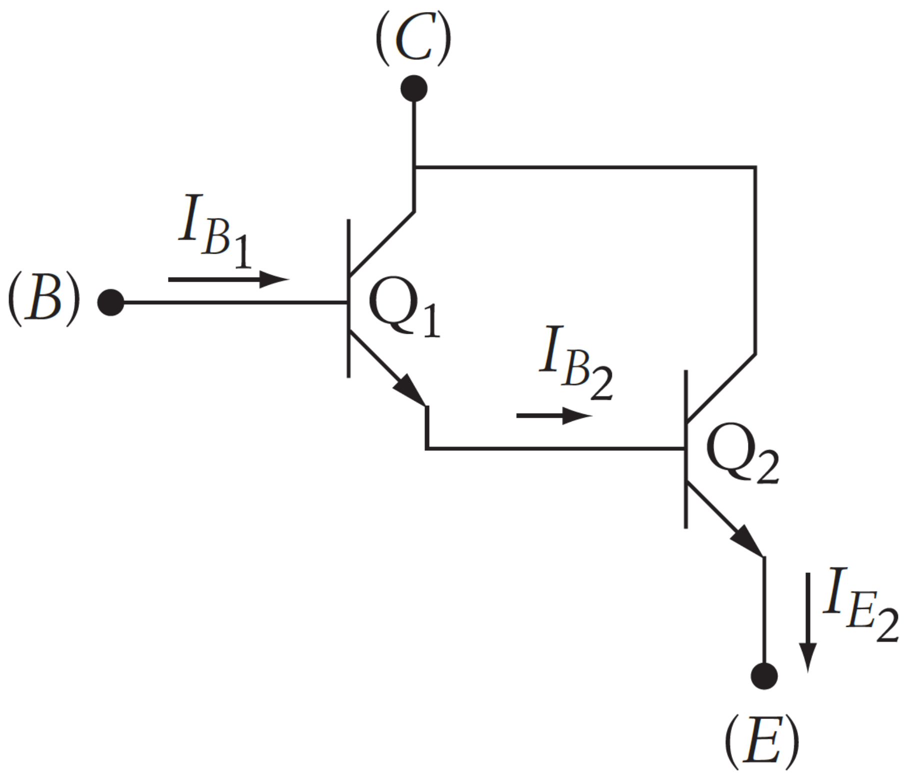




SCR features

- Cheaper production than FET
- They are triggered by a pulse and not by permanent current
- In AC circuits, they are self-extinguishing
- They allow much higher currents and voltages than transistors

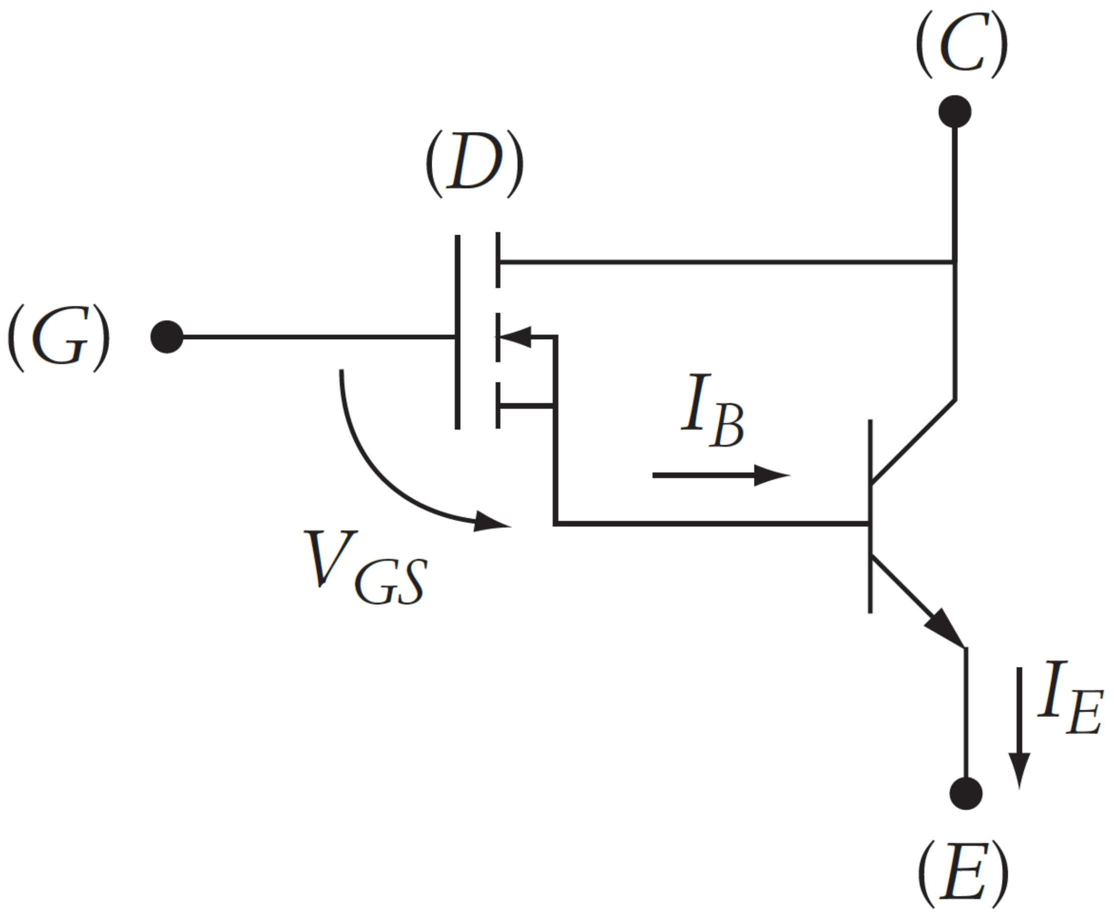
Darligton transistor



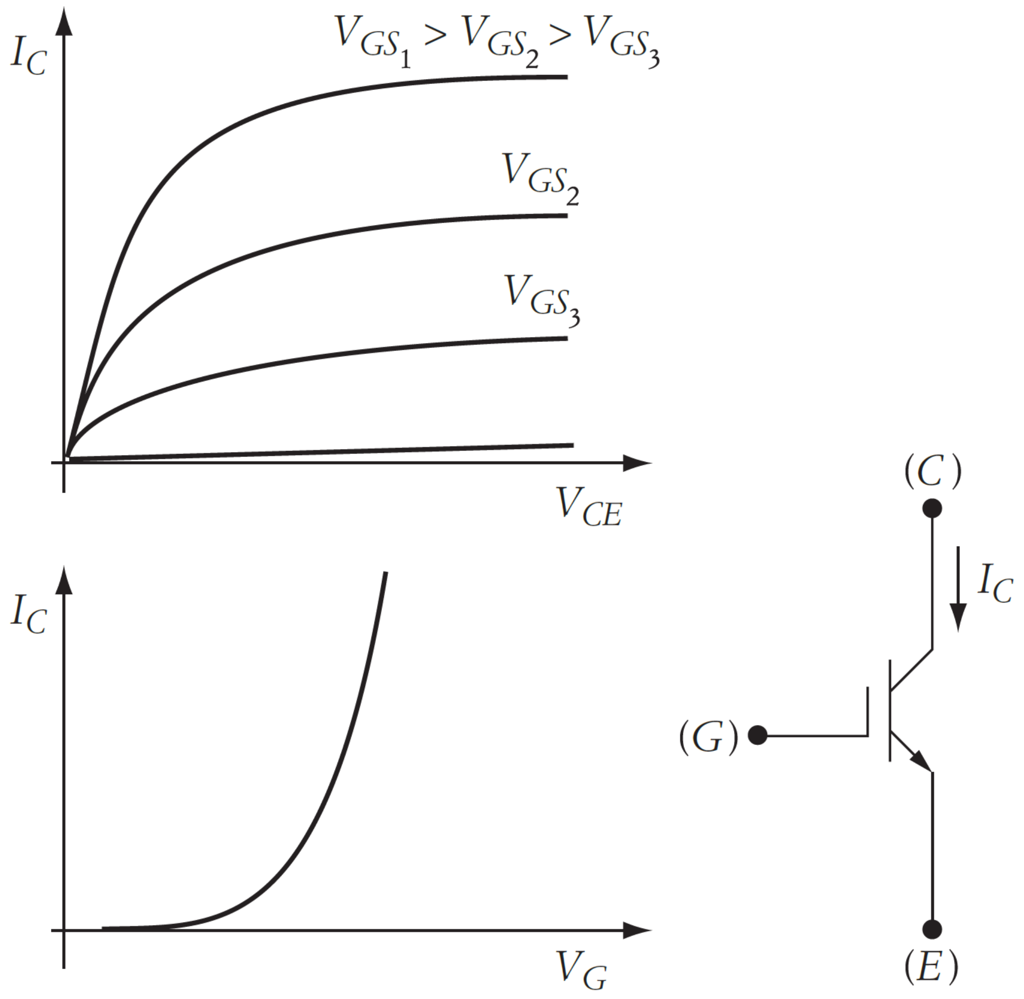
$$I_{E_2} = (1 + \beta_2)I_{B_2} = (1 + \beta_2)(1 + \beta_1)I_{B_1}$$

$$\frac{I_{E_2}}{I_{B_1}} = (1 + \beta_1)(1 + \beta_2)$$

IGBT



IGBT characteristic



Limitations

- Steady-state circuit ratings
- Junction temperature
- Surge current
- Switching time
- Critical rate of rise of current (or maximum di /dt)
- Critical rate of rise of voltage (or maximum dv/dt).