ESC201T: Introduction to Electronics

Lecture 27: Transistors

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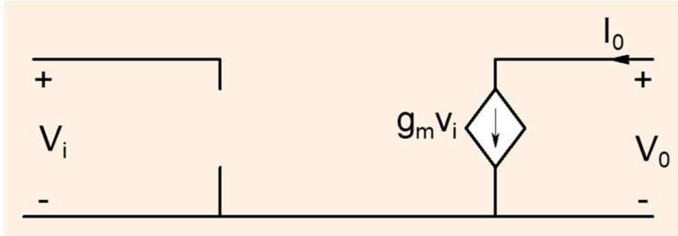
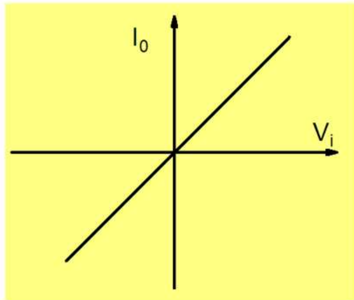
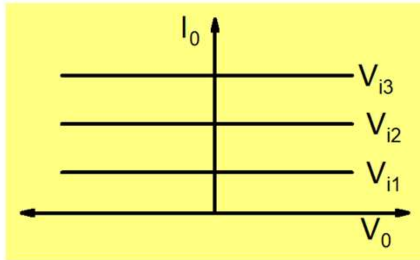
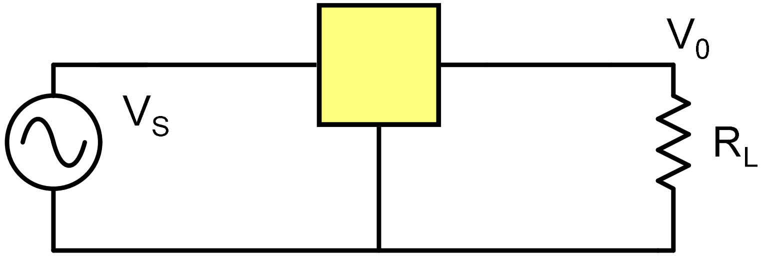
Transistor

Current I_O is much more sensitive to V_{IN} than V_O

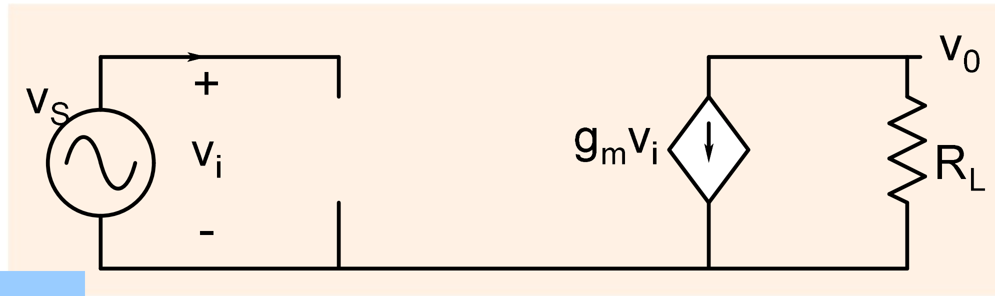




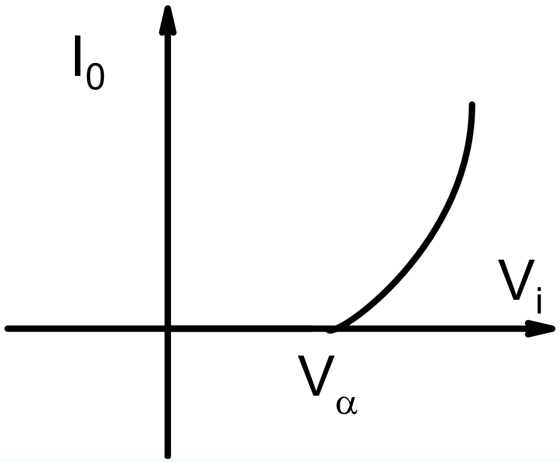


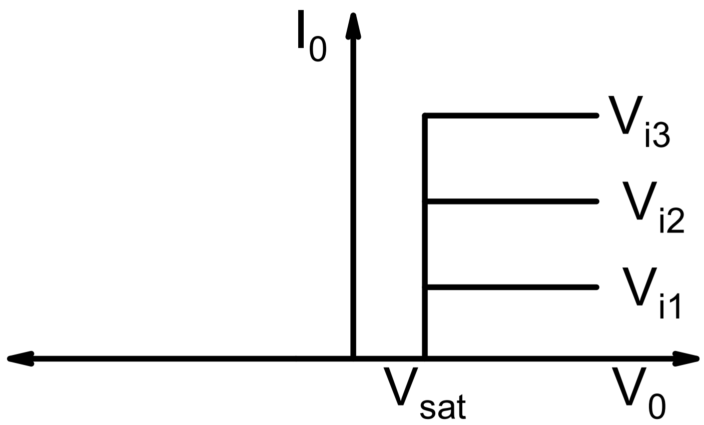


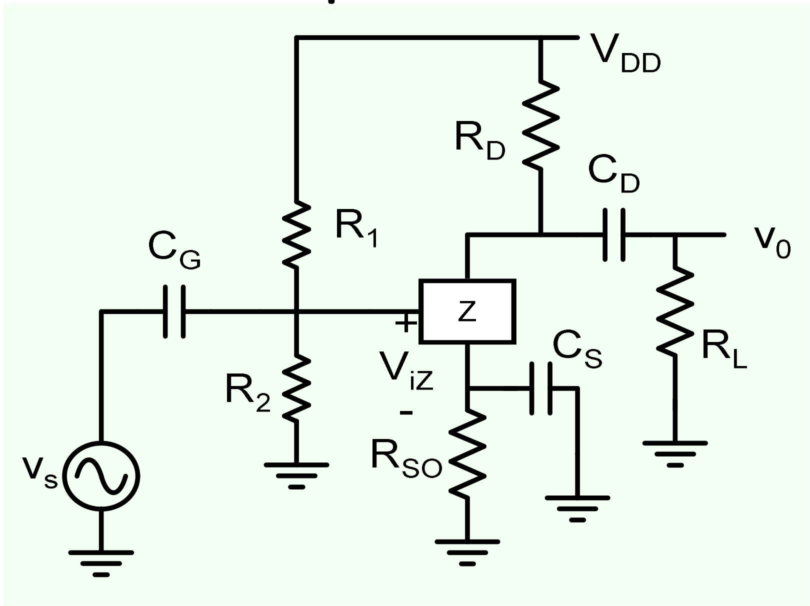
$$A_V = \frac{V_o}{V_s} = -g_m \times R_L$$



Building Amplifiers with non-linear devices



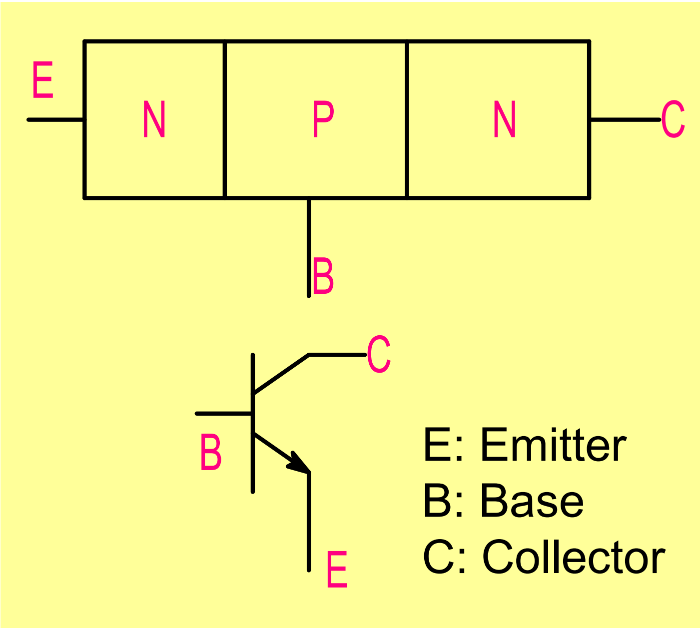




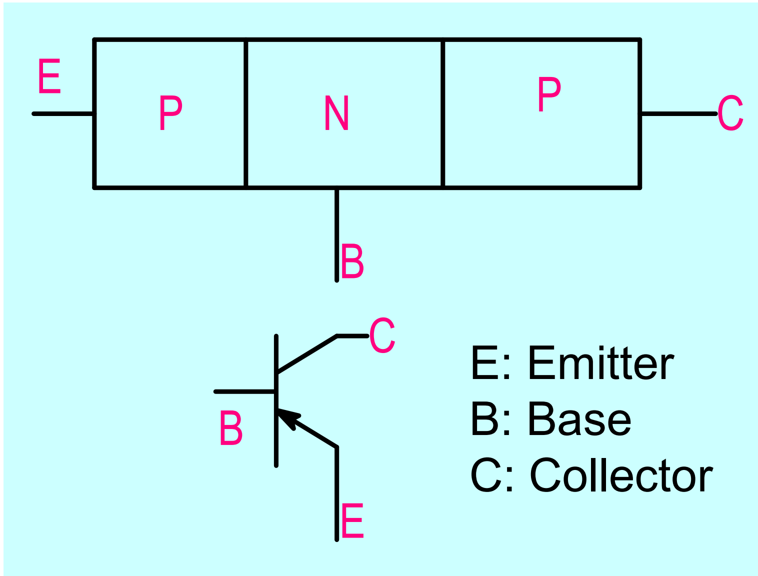
Amplifier will work properly (with small distortion only if we restrict the amplitude of input signal to small values.

How small depends on the nature of non-linearity. The stronger the non-linearity the lesser the signal amplitude.

Bipolar Junction Transistor (BJT)

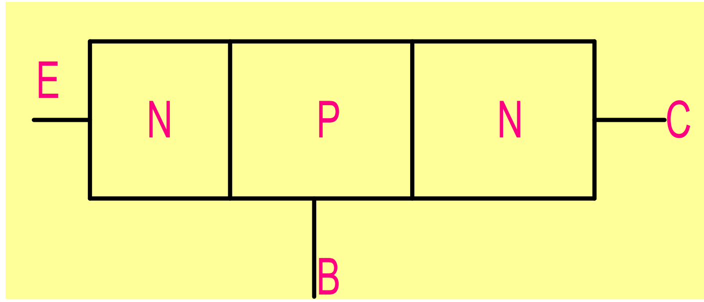


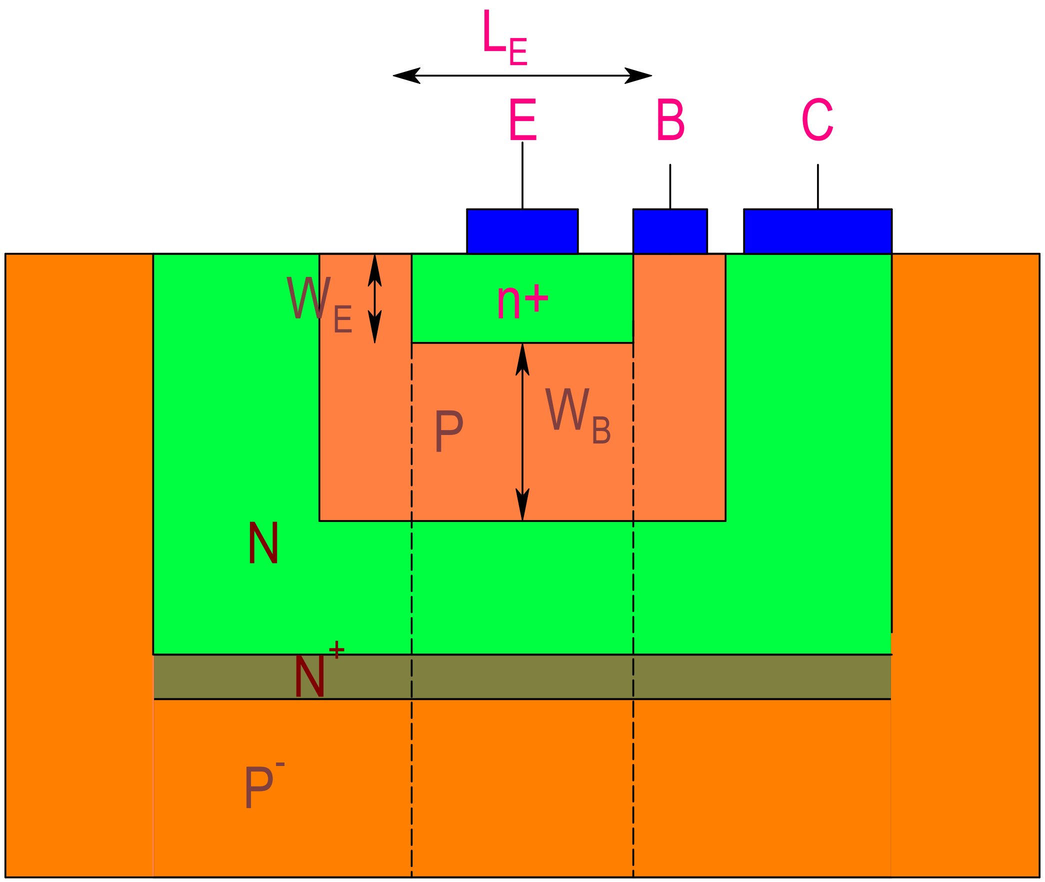
NPN



PNP

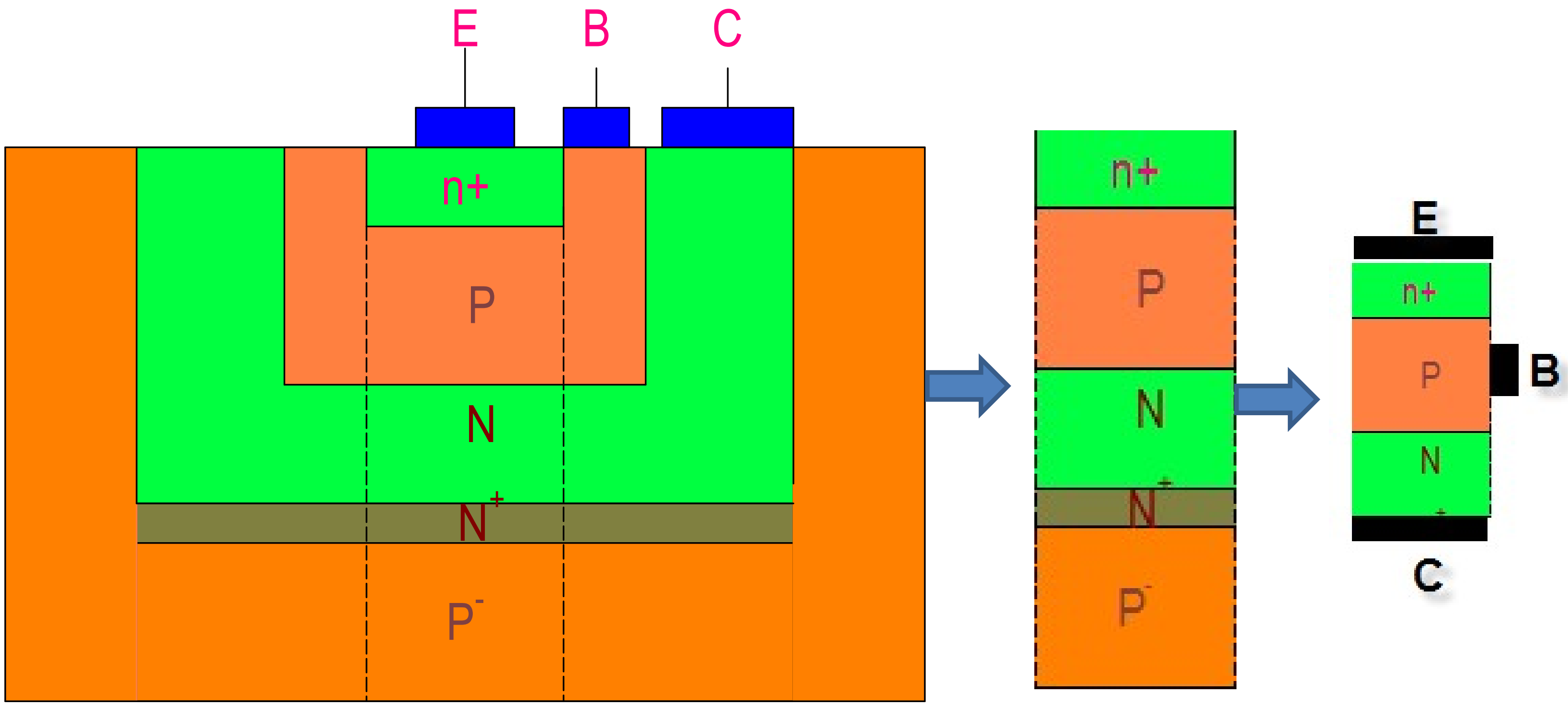
More Realistic View



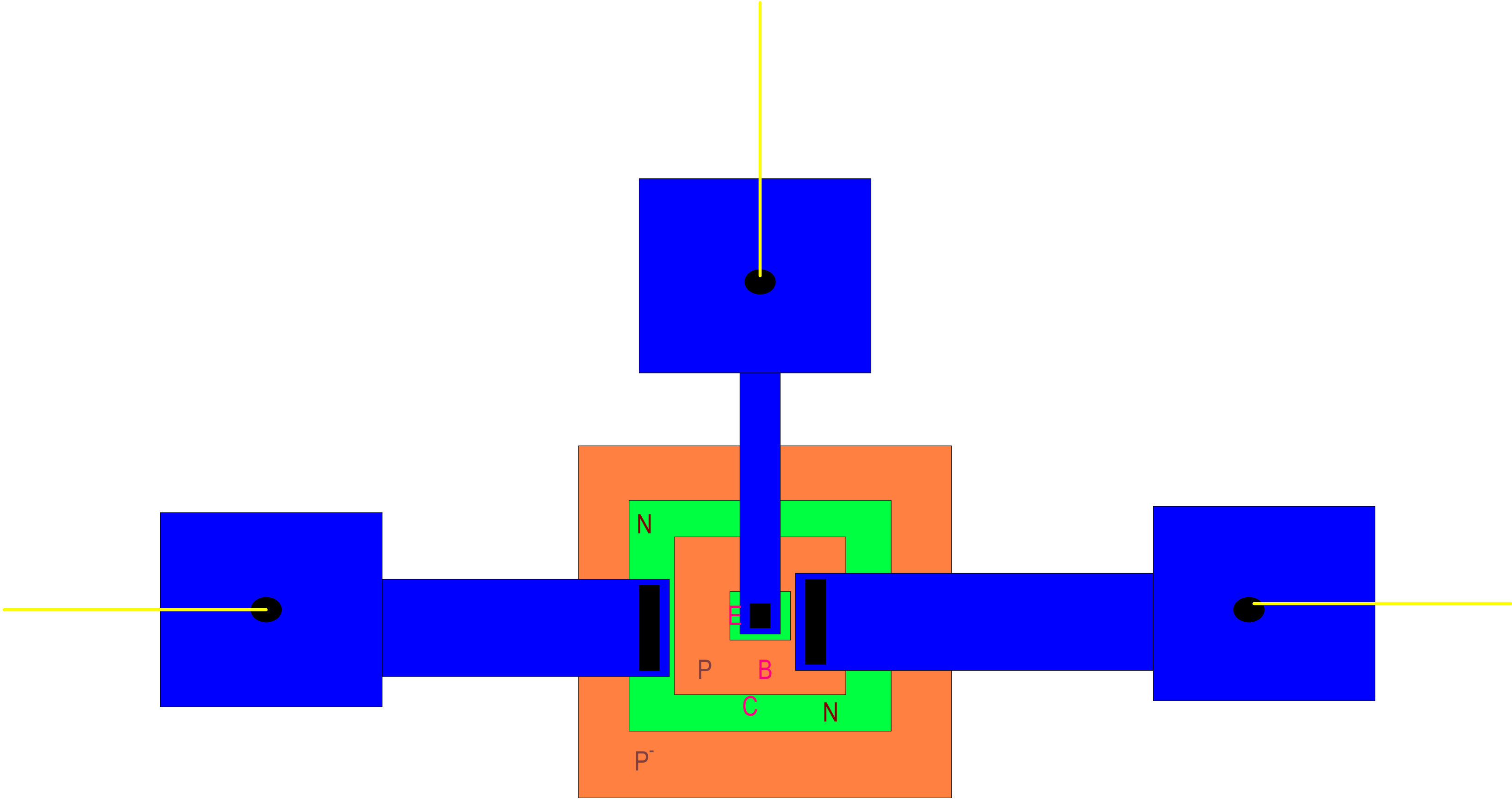


$$N_{DE} \sim 10^{19}\,cm^{-3}$$
$$N_{AB} \sim 10^{17}\,cm^{-3}$$
$$N_{DC} \sim 10^{16}\,cm^{-3}$$
$$W_B \sim 2000\,A^{\circ}$$
$$W_E \sim 1000\,A^{\circ}$$
$$L_E \sim 1\,\mu m$$

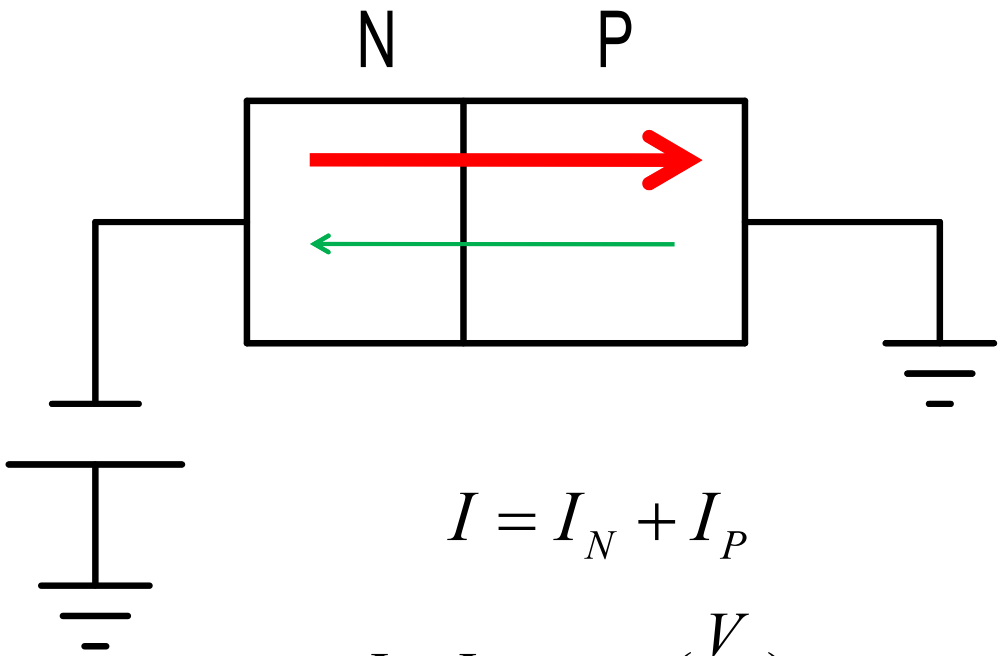
BJT is not symmetric: emitter and collector cannot be simply interchanged


E
B
C
n+
P
N
N+
P-
n+
P
N
N+
P-
E
n+
P
B
N
C

Top View



Background

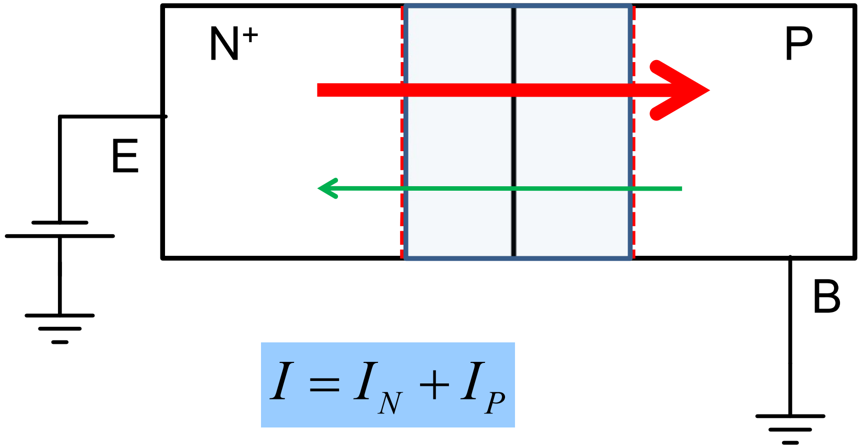


$$I = I_N + I_P$$

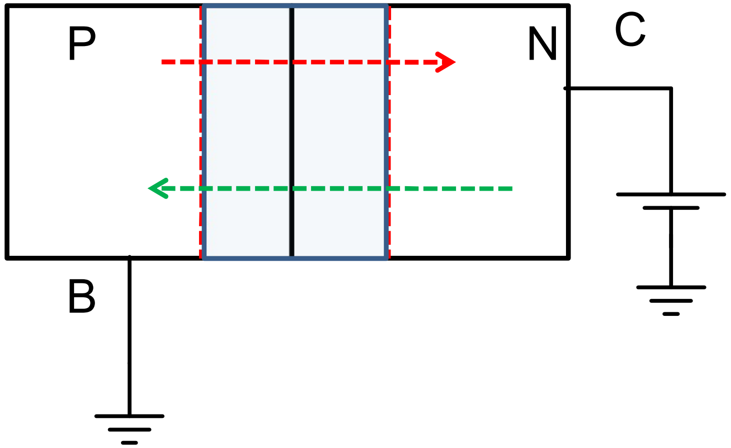
$$I_N ; I_P \propto \exp(\frac{V}{V_T})$$

If doping in N region is much larger than doping in p region then $I_N >> I_P$

Basic Transistor Operation



$$I = I_N + I_P$$



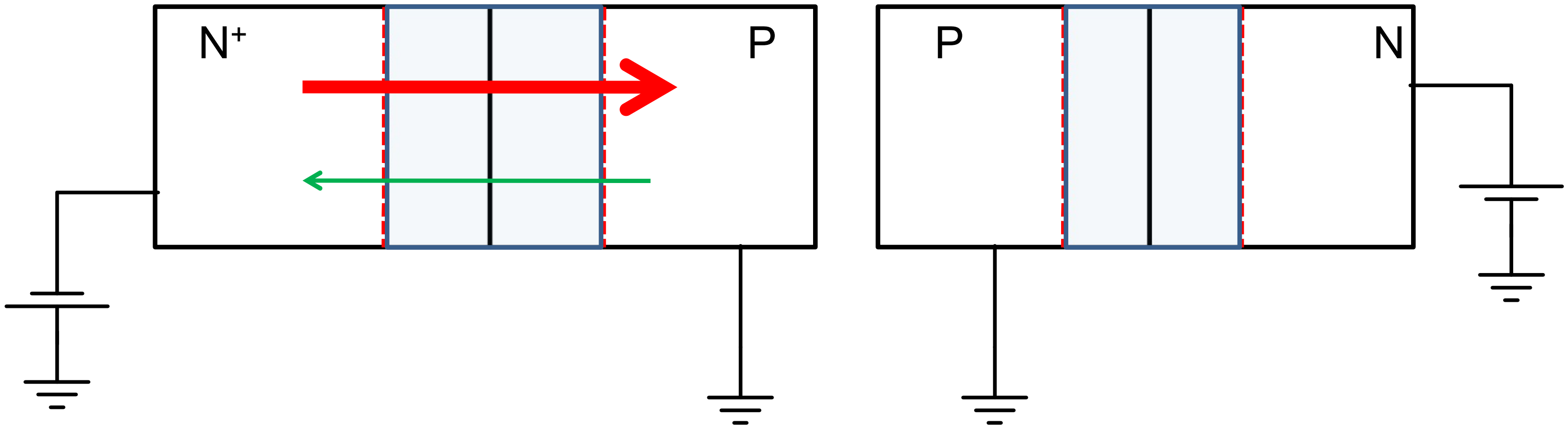
We will assume that doping in emitter is much more than base so that electron current is much larger than hole current

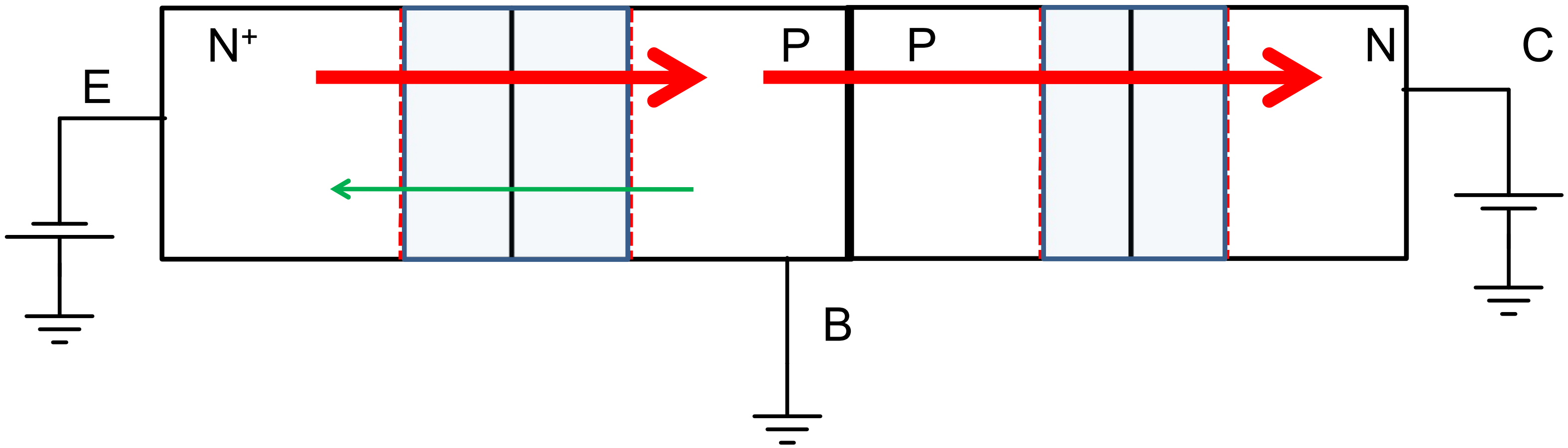
$$I_N >> I_P$$

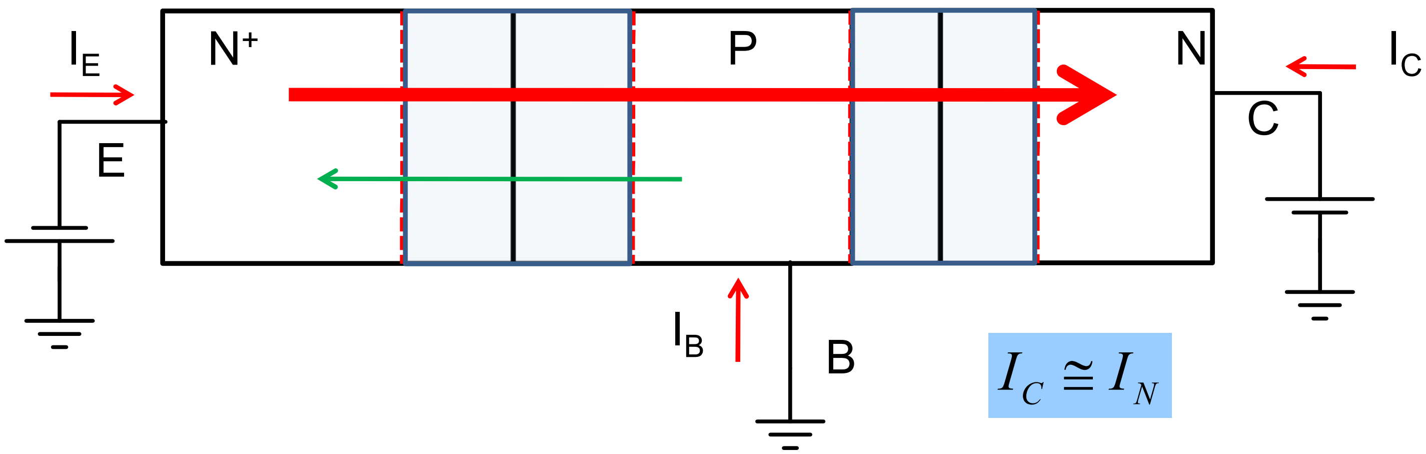
In the reverse biased junction current is small because there are very few electrons in P and holes in N-region

Basic Transistor Operation

$$I = I_N + I_P$$





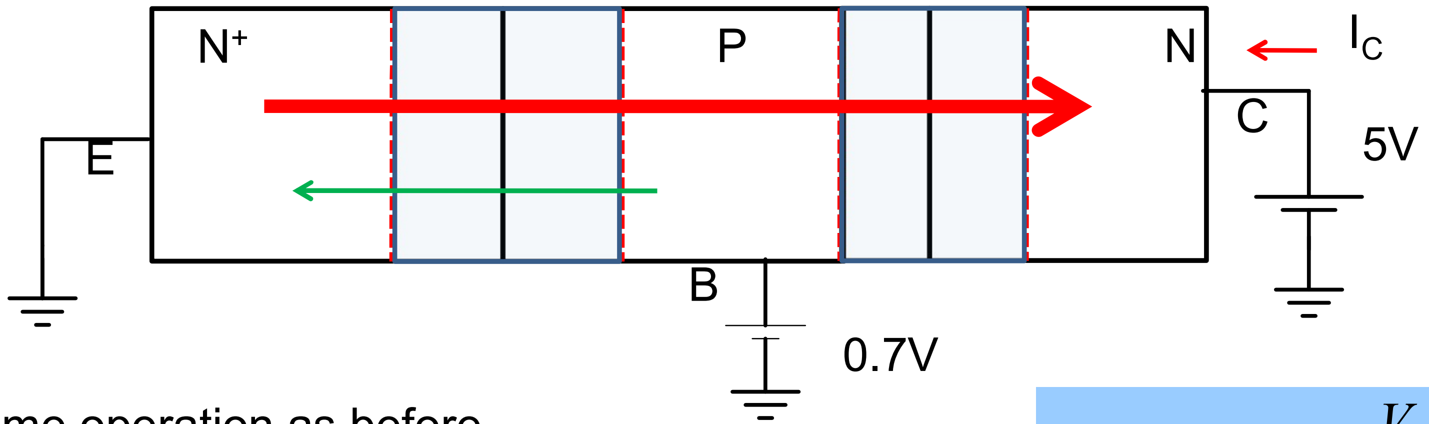


$$I_C \cong I_N$$

$$I_E = I_N + I_P$$

$$I_B \cong I_P$$

$$\text{Current Gain}: \quad \beta = \frac{I_C}{I_B} = \frac{I_N}{I_P} >> 1$$

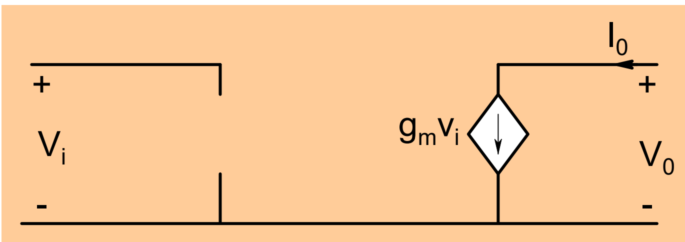


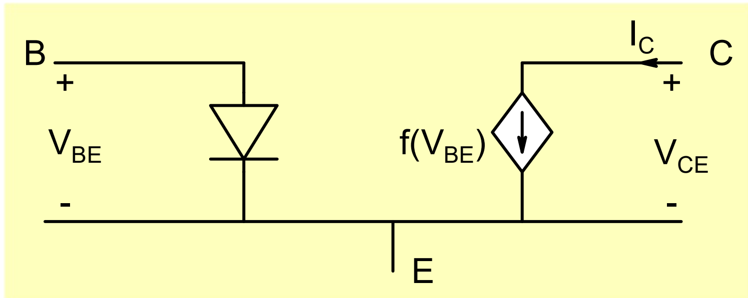
Same operation as before

$$I_C = I_N \propto \exp\left(\frac{V_{BE}}{V_T}\right)$$

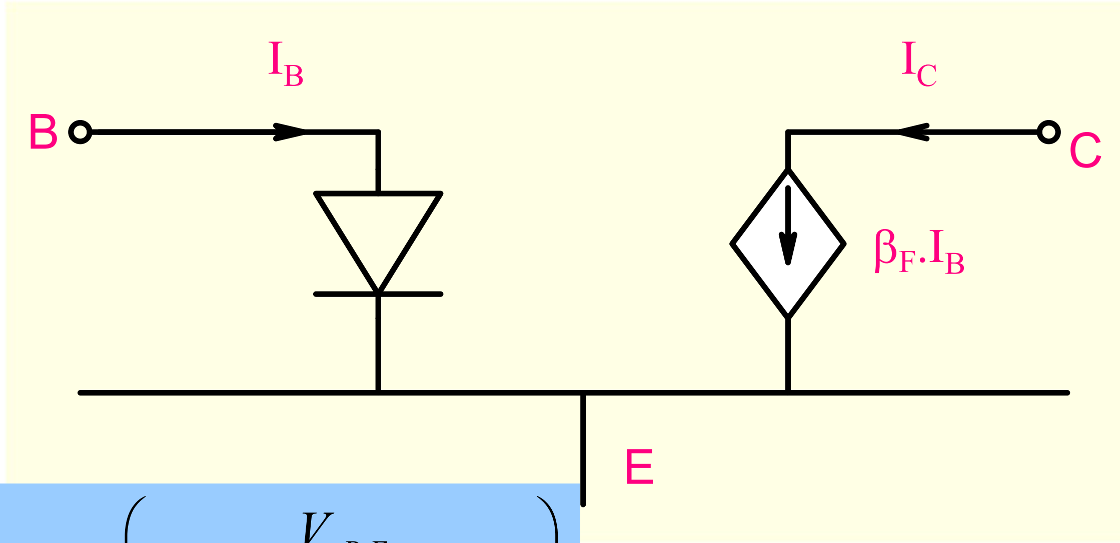
Transistor action

Current is affected by base-emitter voltage and not by collector-base voltage





Alternative representation



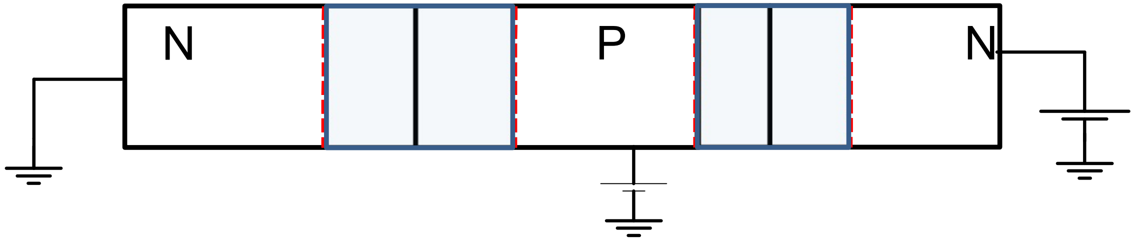
$$\beta = \frac{I_C}{I_B}$$

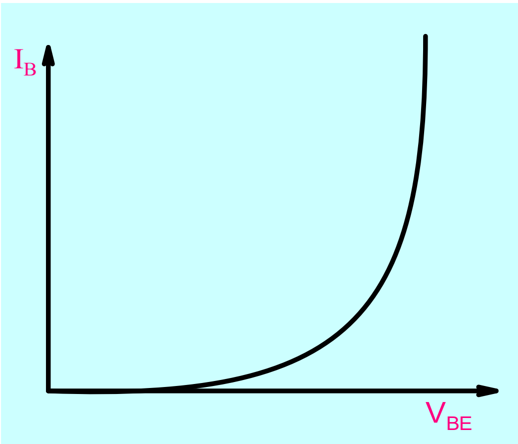
$$I_B = I_{BS}\left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right)$$

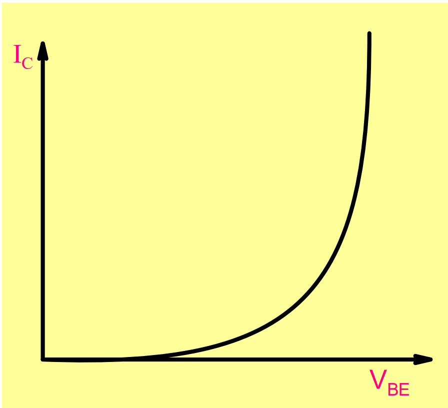
$$I_C = I_S\left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right)$$

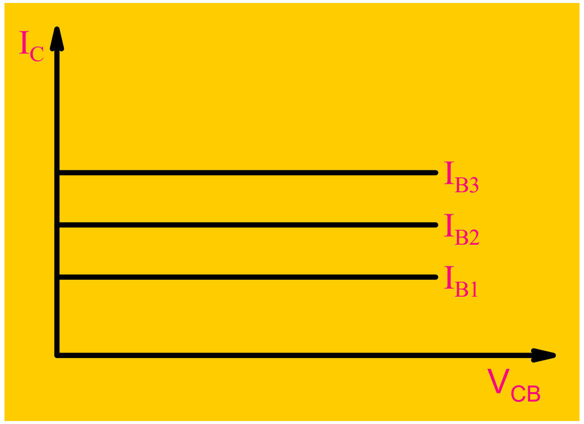
$$I_B = \frac{I_C}{\beta_F}$$

Transistor Characteristics

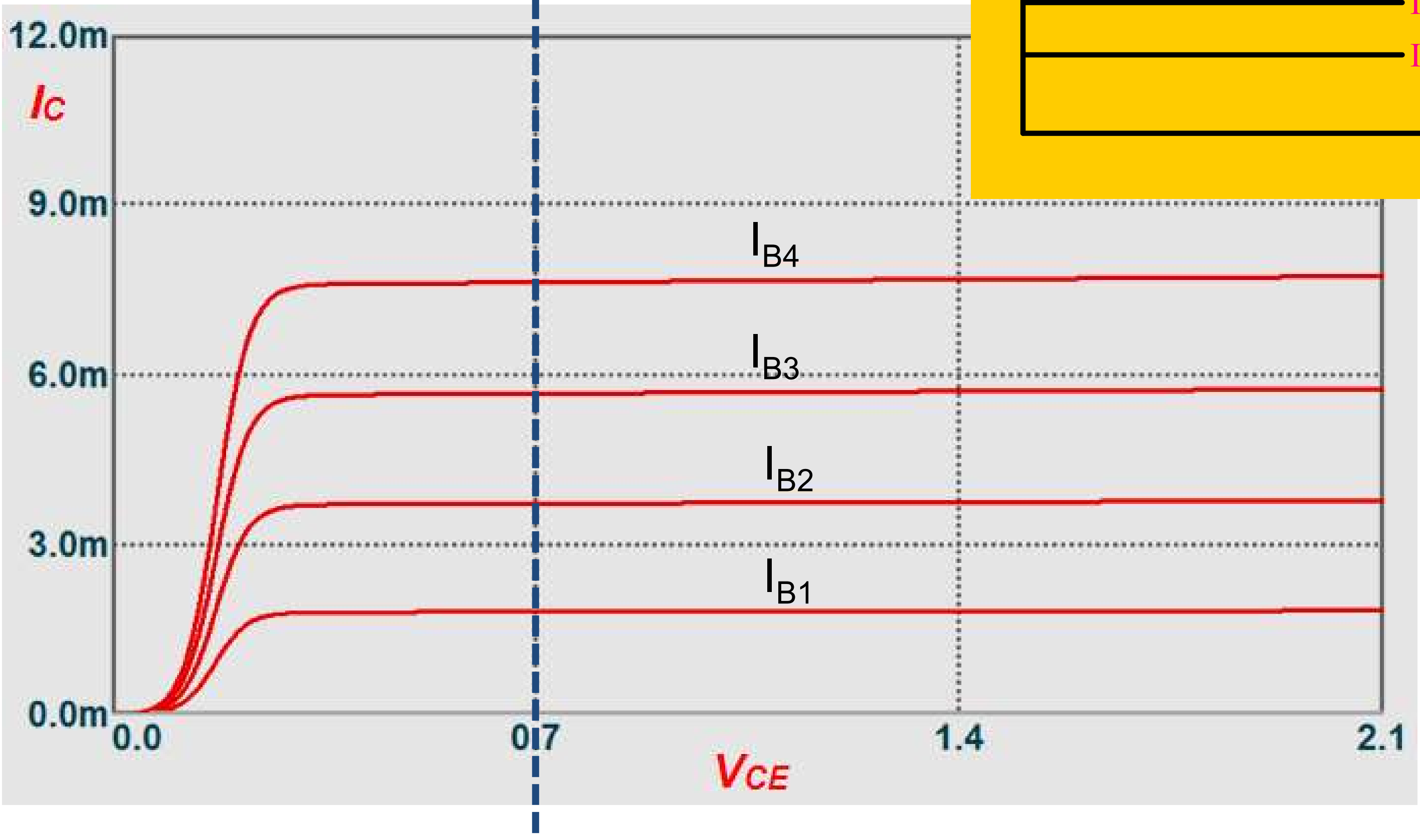


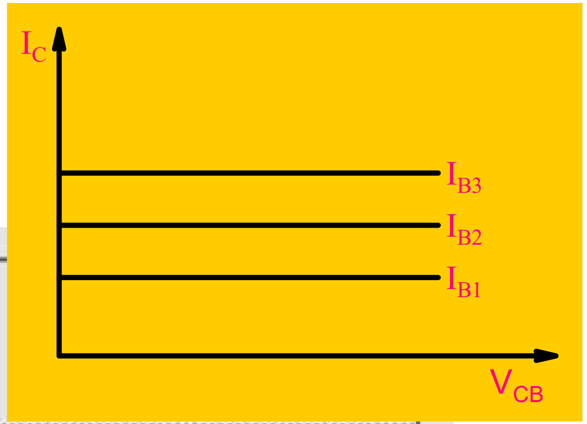






Output Characteristics of the transistor



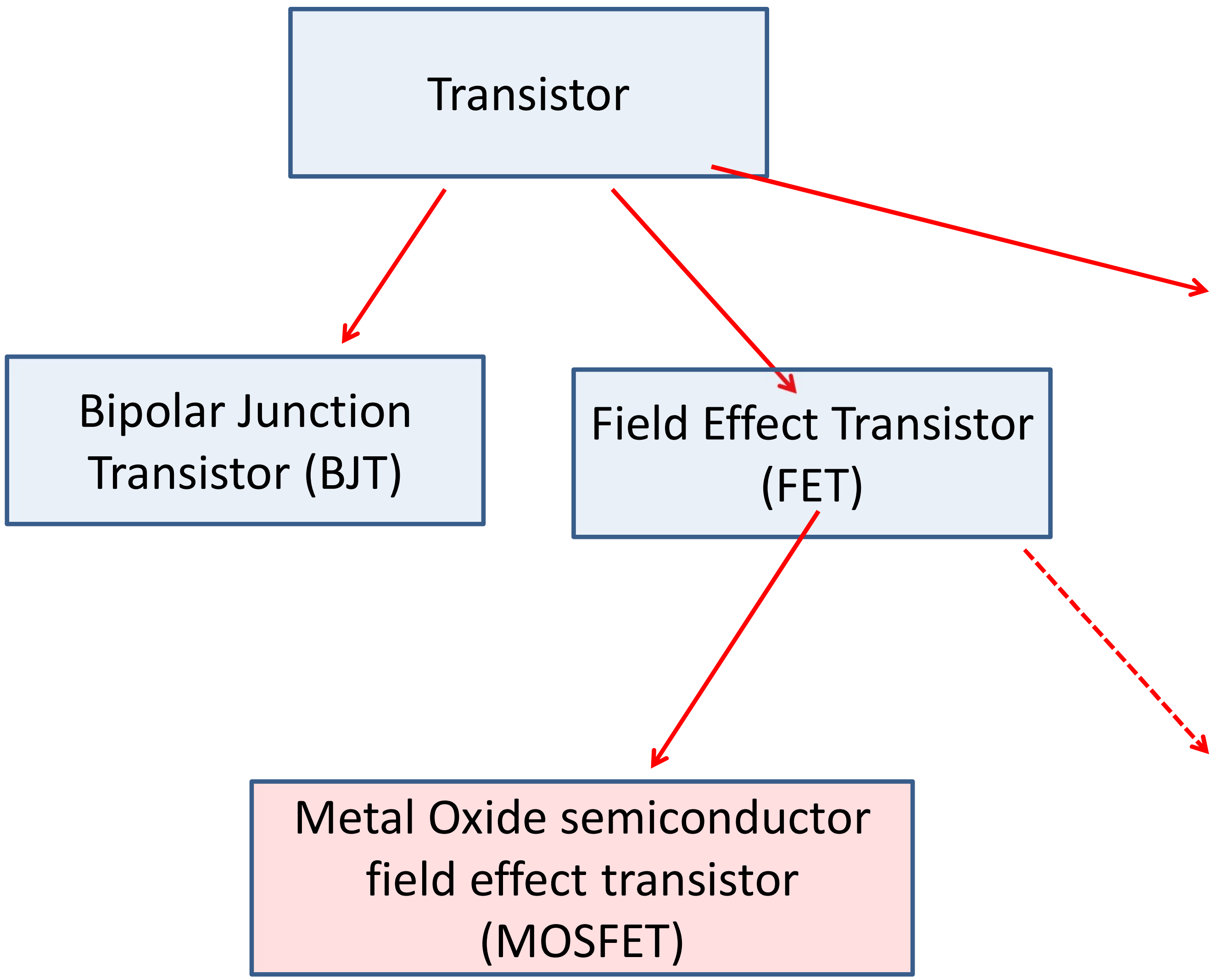


$V_{CE} = V_{CB} + V_{BE}$

$= V_{BE} - V_{BC}$

$$V_{CE} = 0.7 - V_{BC}$$

Transistors



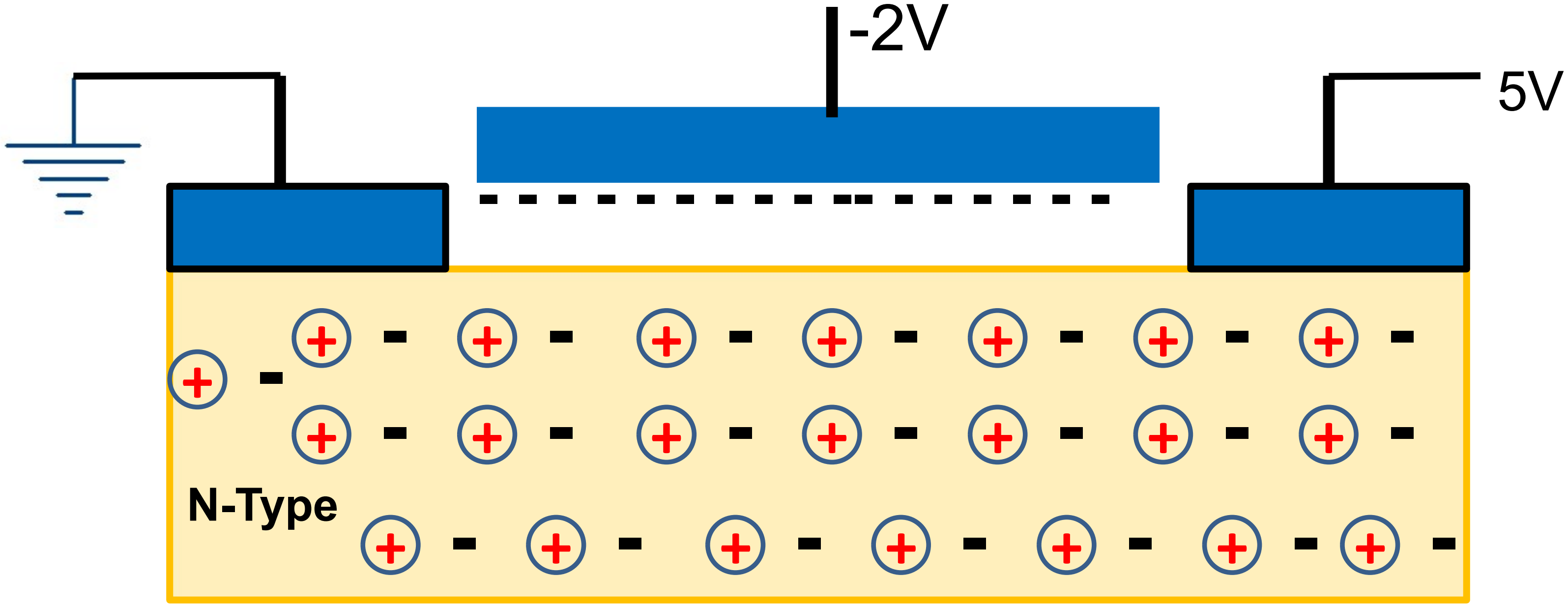
Transistor

Current I_O is much more sensitive to V_{IN} than V_O

$$\frac{\partial I_O}{\partial V_{in}} >> \frac{\partial I_O}{\partial V_o}$$

Field Effect Principle

$$\frac{\partial I_O}{\partial V_{in}} >> \frac{\partial I_O}{\partial V_o}$$



Modulation of conductivity using electric field

Transconductance

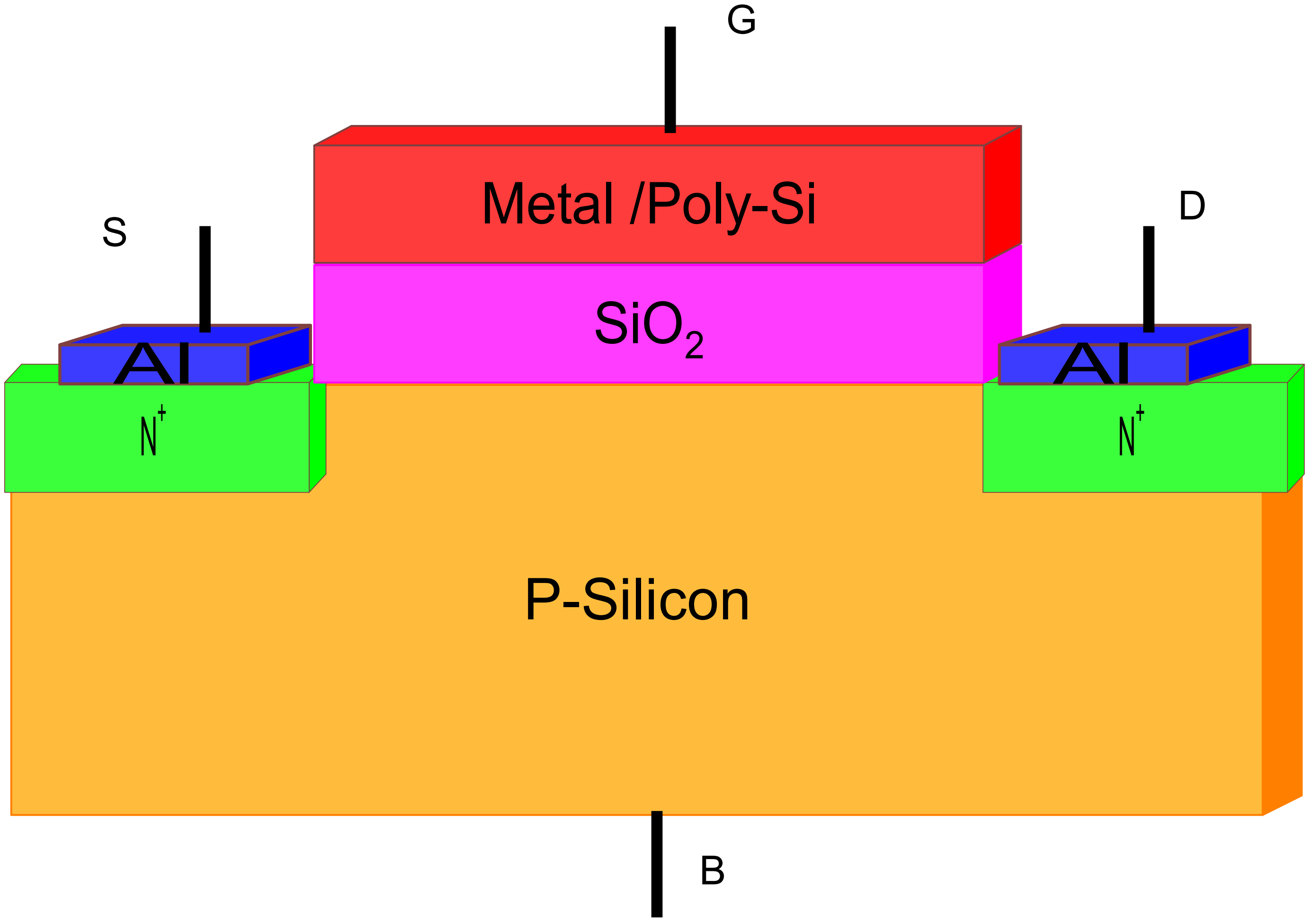
Jan. 28, 1930. J. E. LILIENFELD 1,745,175

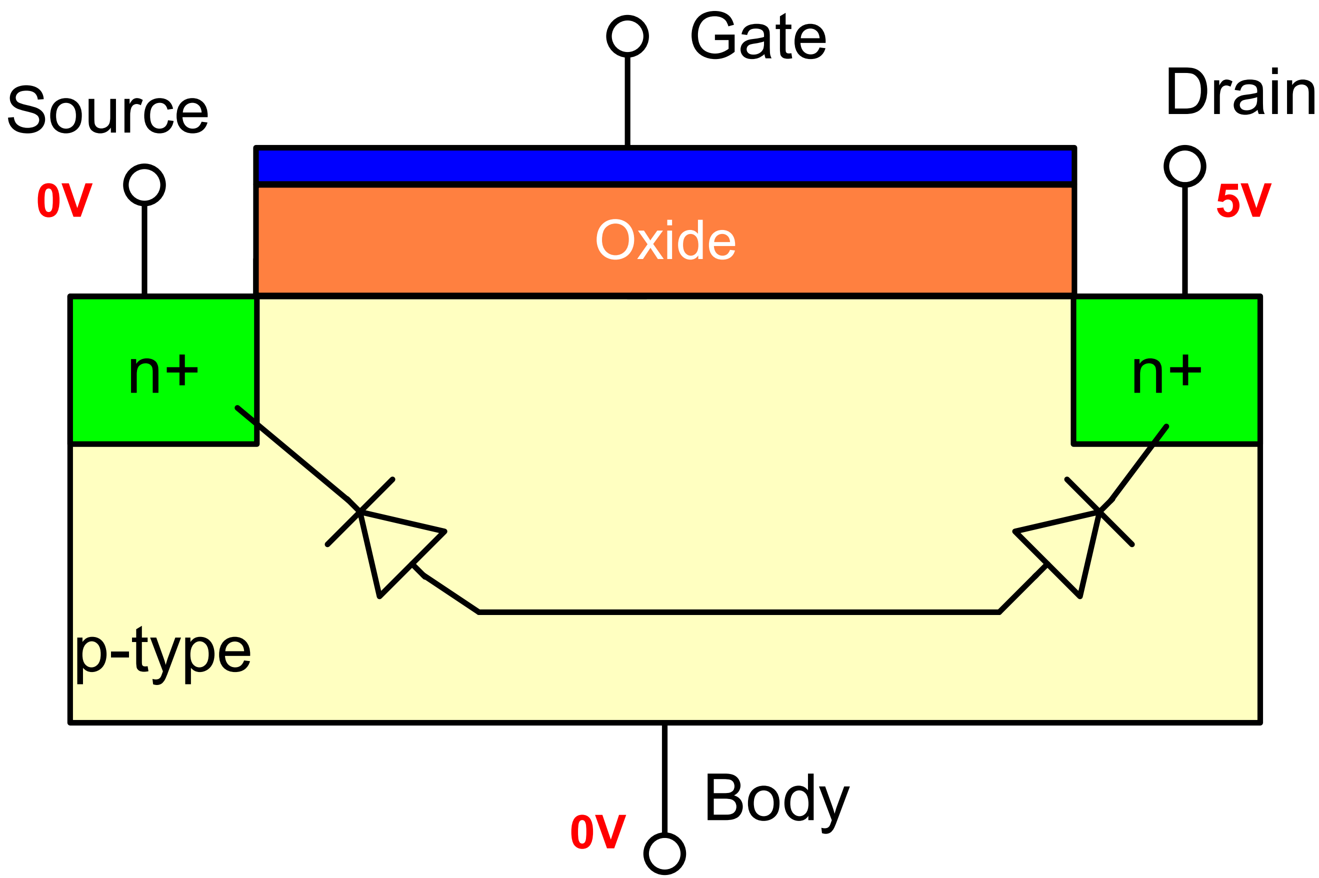
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926

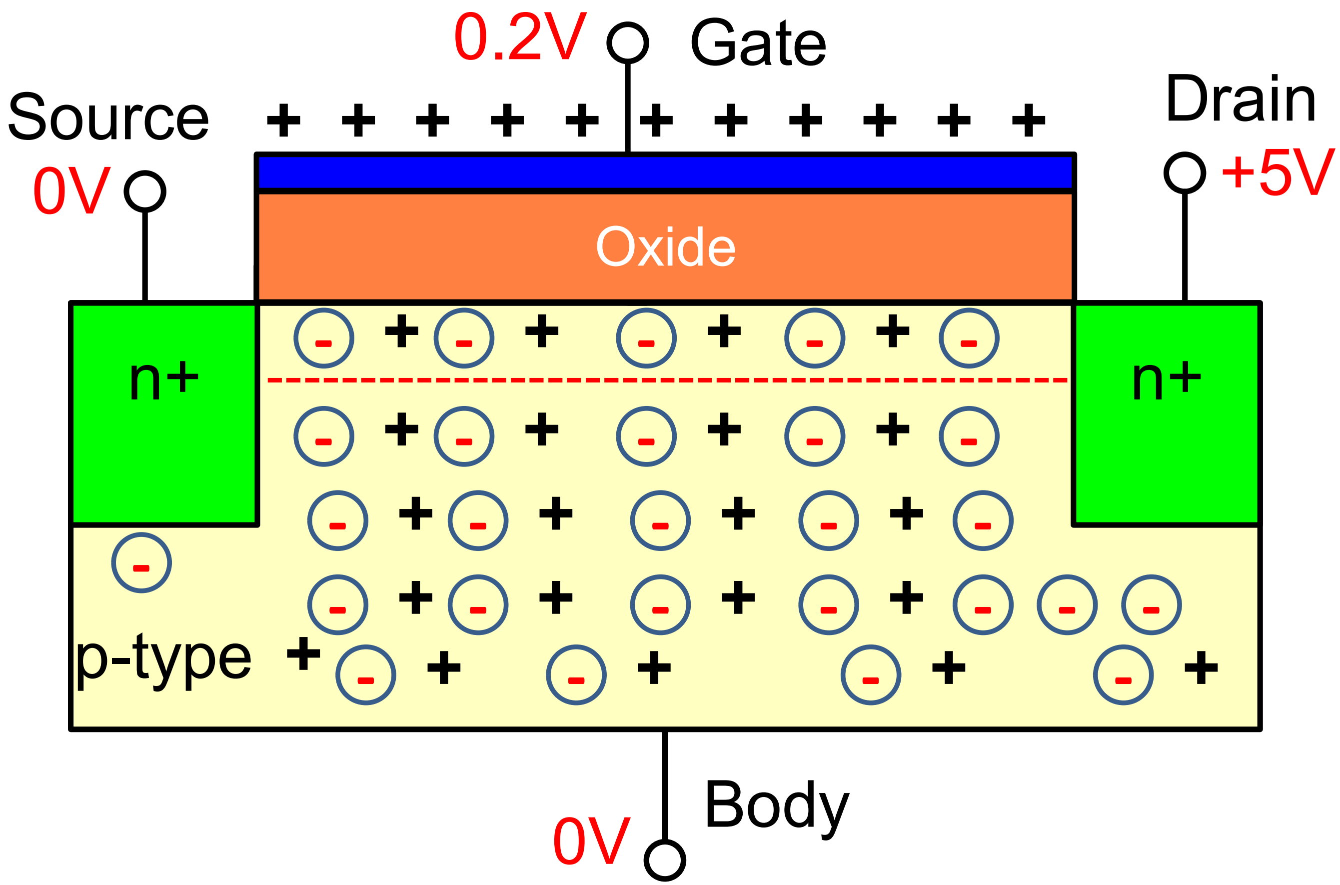
The invention relates to a method of and apparatus for controlling the flow of an electric current between two terminals of an electrically conducting solid by establishing a third potential between said terminals; and is particularly adaptable to the amplification of oscillating currents such as prevail, for example, in radio communication. Heretofore, thermionic tubes or valves have been generally employed for this purpose; and the present invention has for its object to dispense entirely with devices relying upon the transmission of electrons thru an evacuated space and especially to devices of this character wherein the electrons are given off from an incandescent filament. The invention has for a further object a simple, substantial and inexpensive relay or amplifier not involving the use of excessive voltages, and

NMOS Enhancement mode transistor: Inversion Mode Transistor

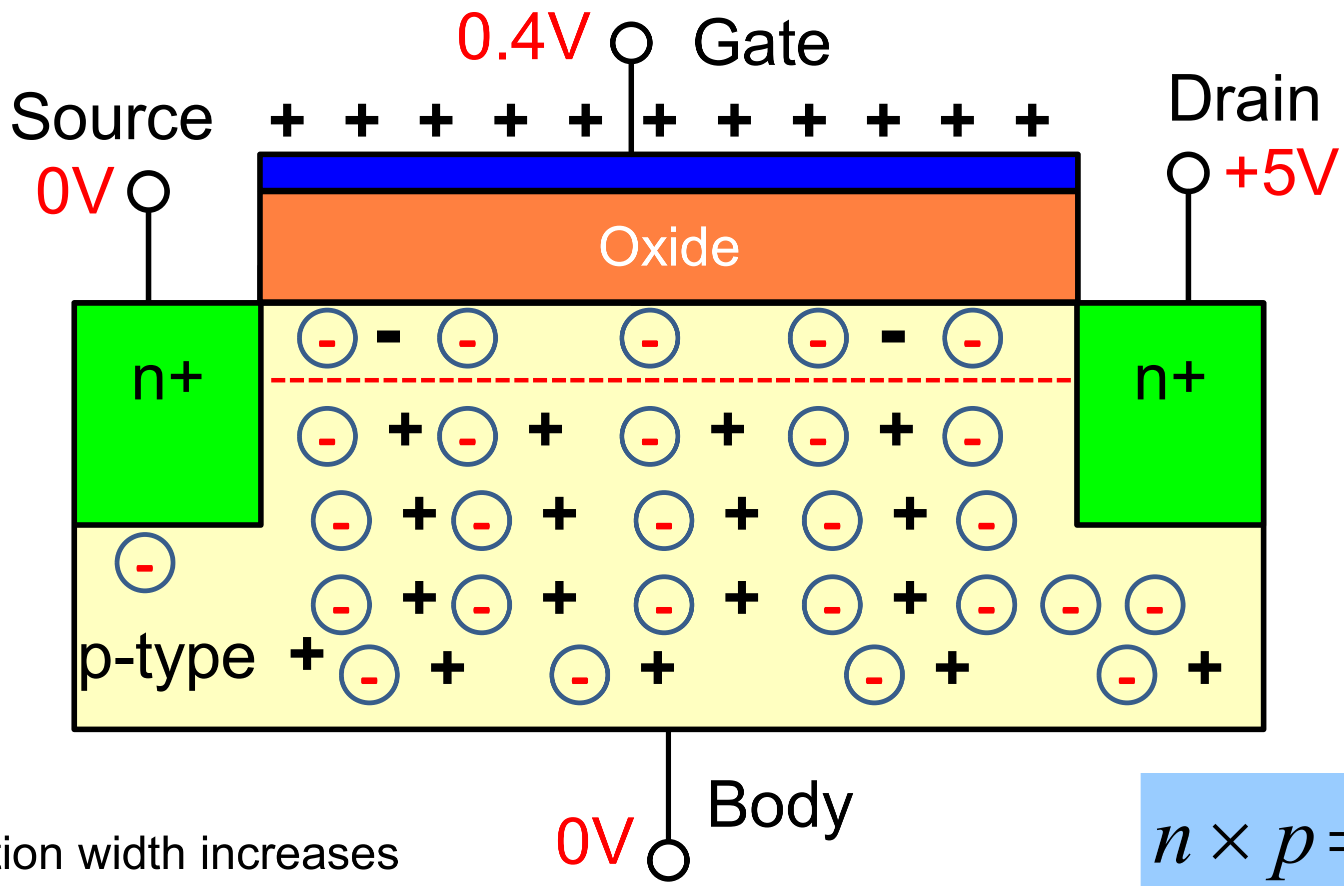




No channel exists when gate voltage is zero and current is zero as well.



Depletion Region is formed near the Si/SiO_2 interface

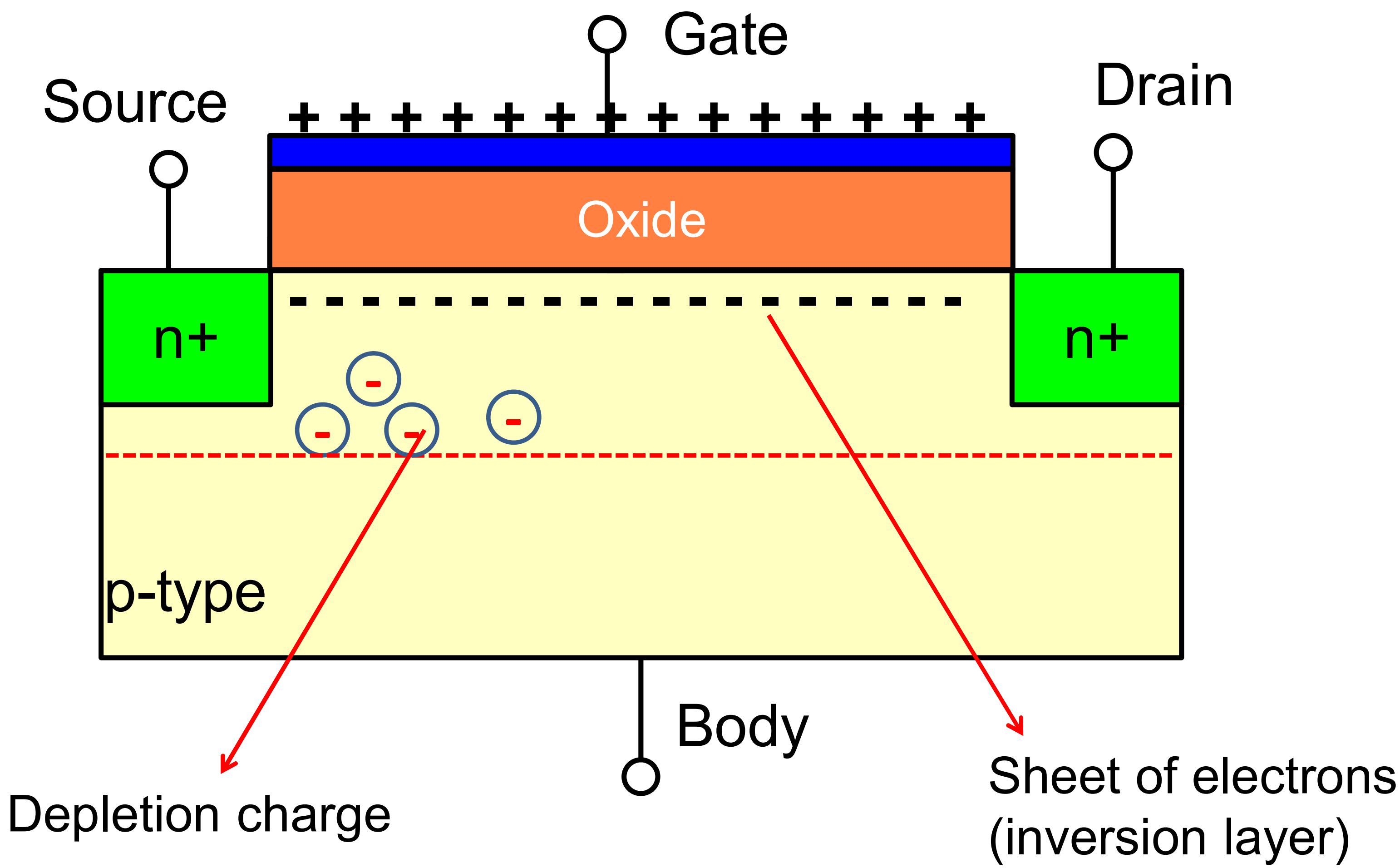


$$n \times p = n_i^2$$

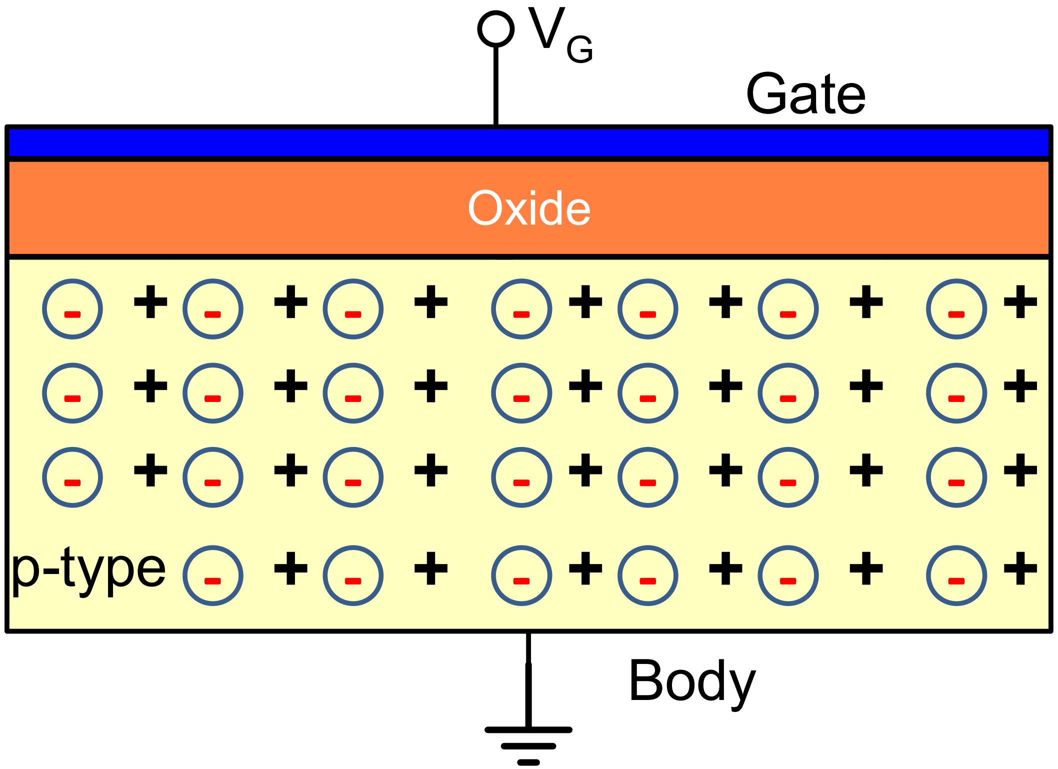
Depletion width increases

But something interesting happens: electron density at the surface also increases

At a sufficiently large voltage (>V_{THN}) a channel of electrons forms at the Si/SiO2 interface.



Conductivity modulation at the surface?

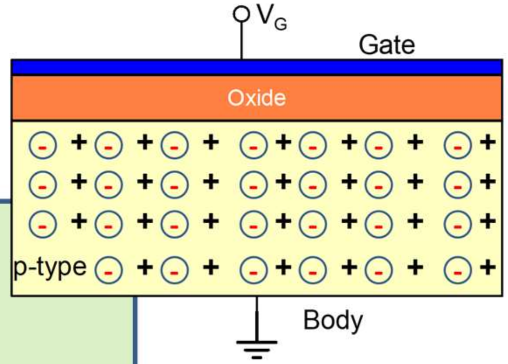


$p = N_A = 10^{16} cm^{-3}$

$n = \frac{n_i^2}{p} \cong 10^4 cm^{-3}$

Field Effect…

$$n_s \times p_s = n_1^{\,2} \cong 10^{20}\, cm^{-3}$$



$V_G \uparrow$ 0V → V_T

P_s: 10^{16} 10^{15} .... 10^{10} --- 10^{8} .... 10^{4}

n_s: 10^{4} 10^{5} .... 10^{10} --- 10^{12} .... 10^{16} → 10^{17} .....

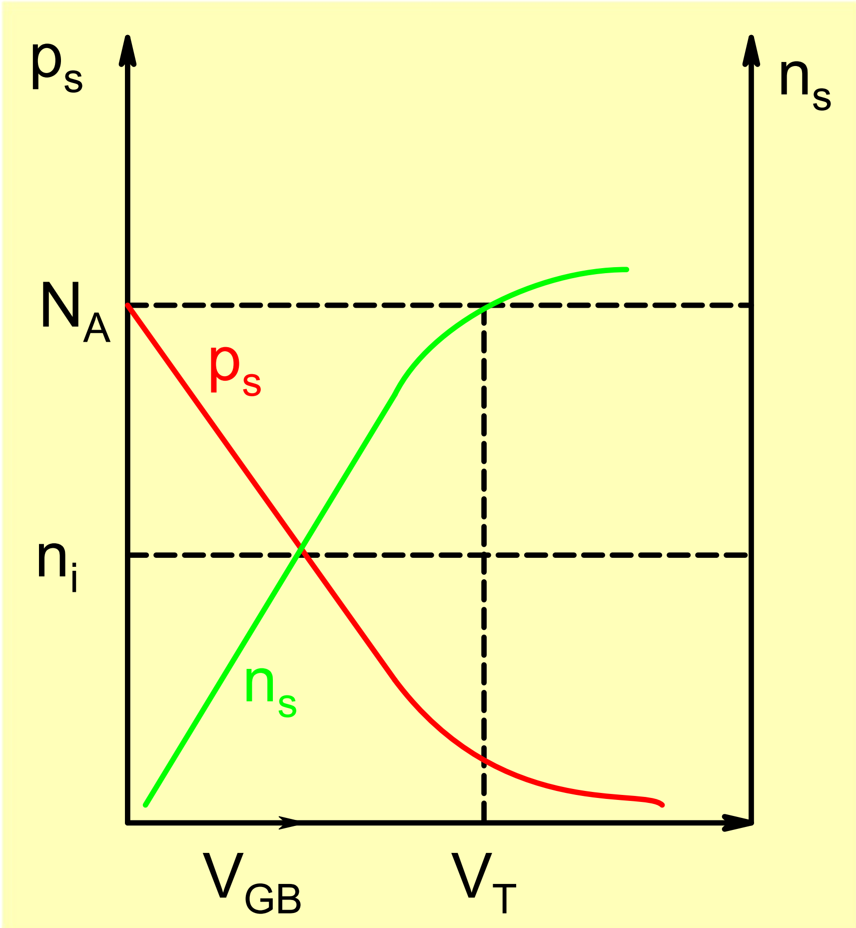
Surface P-Type ← Intrinsic

Inverted → Surface N-Type

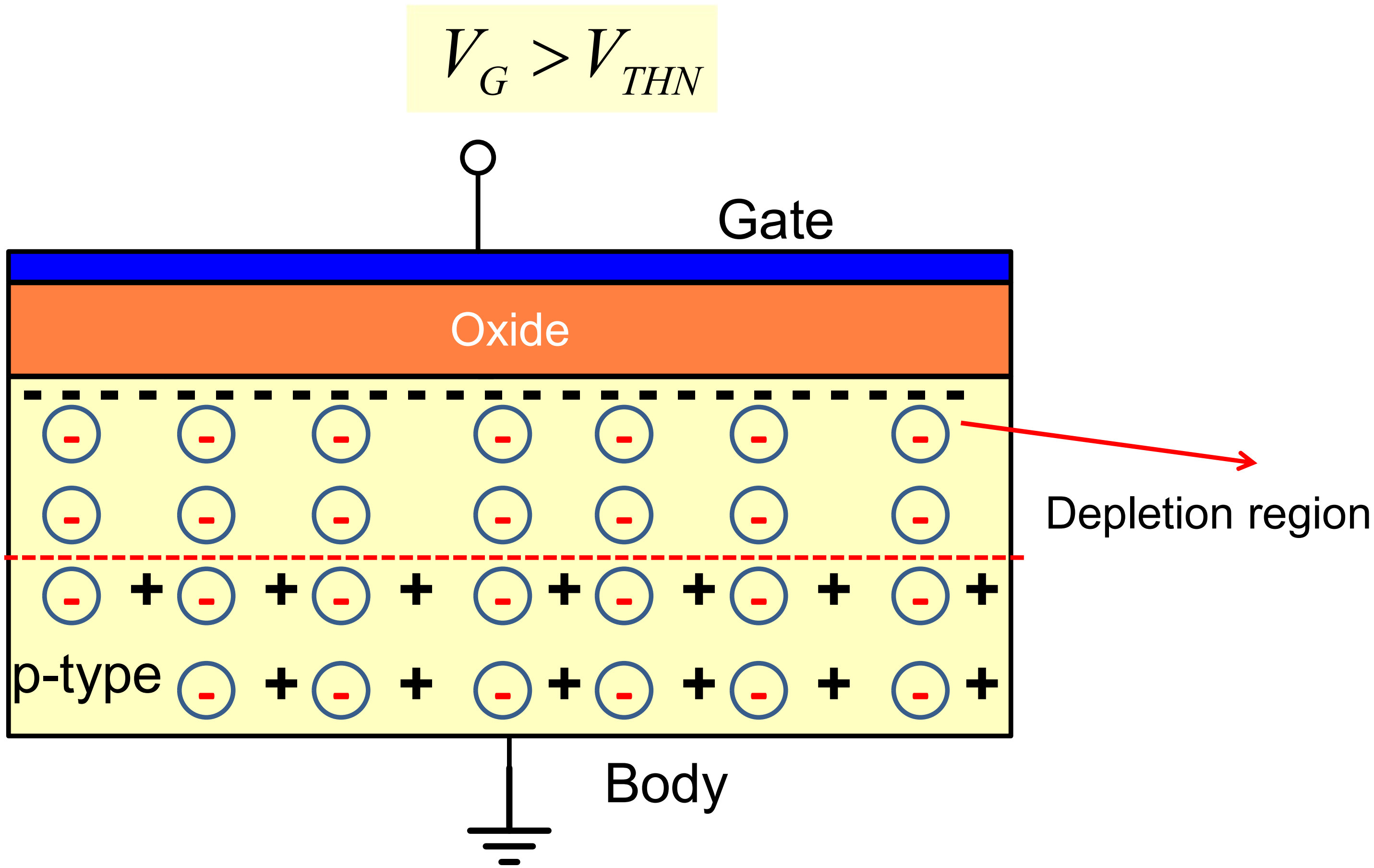
Strong Inversion

Surface carrier density can be changed from P-type to N-type

Surface Carrier Density

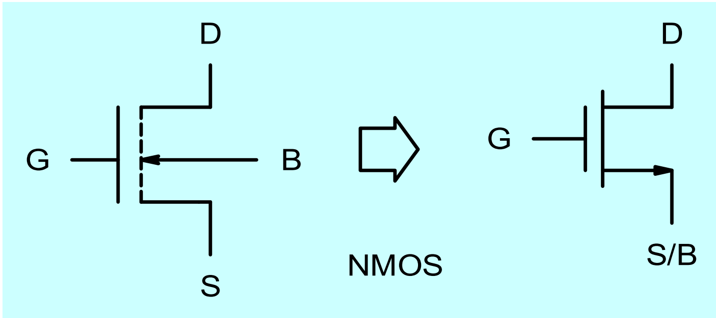


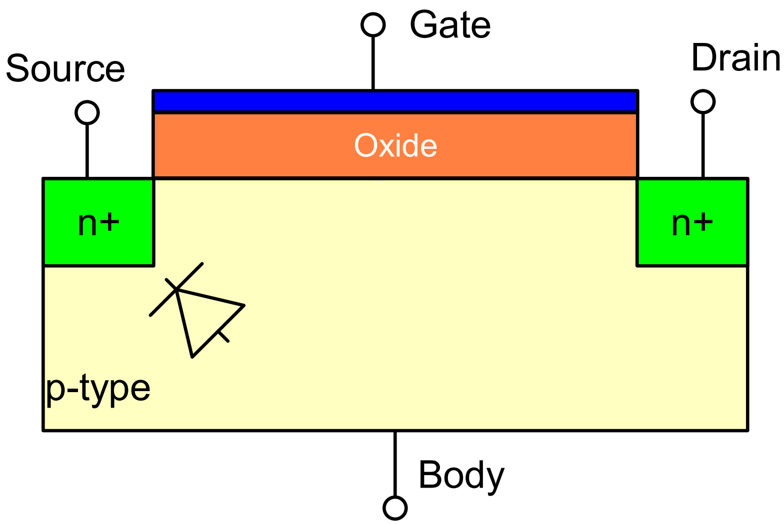
Strong Inversion

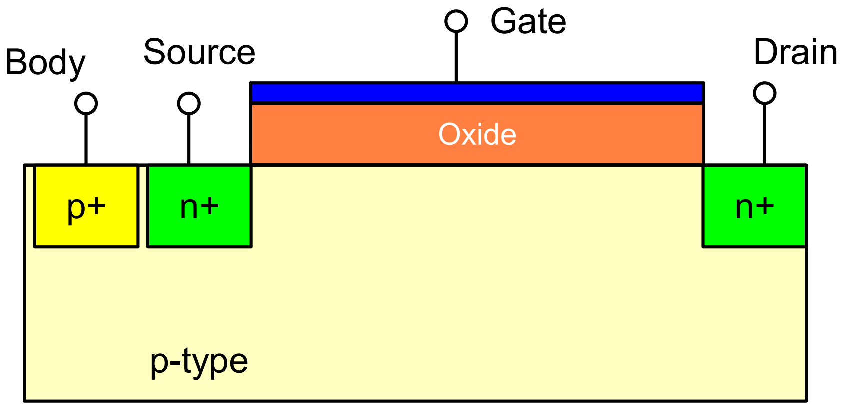


Electrons are accumulated at the surface $n_S >> N_A$

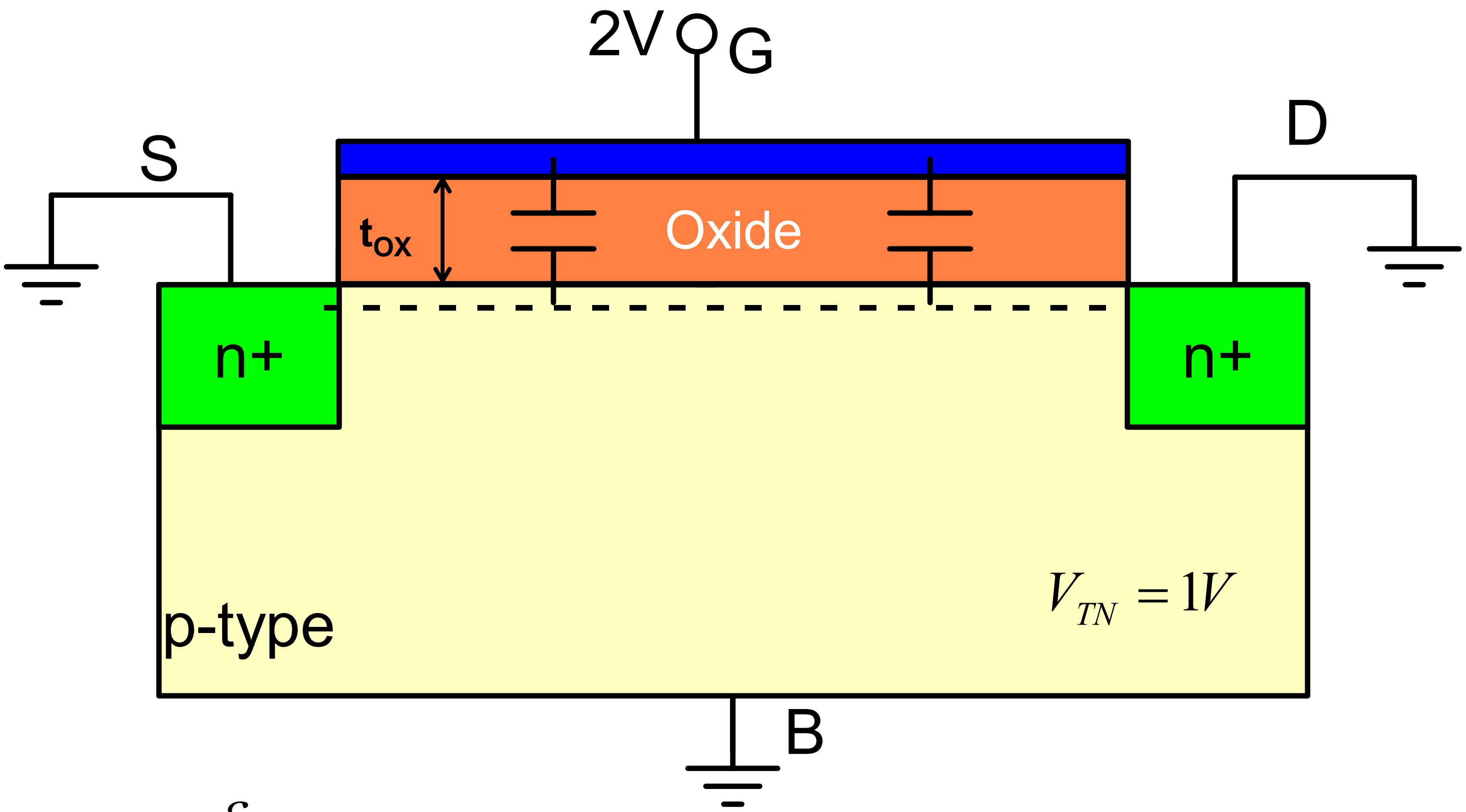
Simplified Symbols and structure





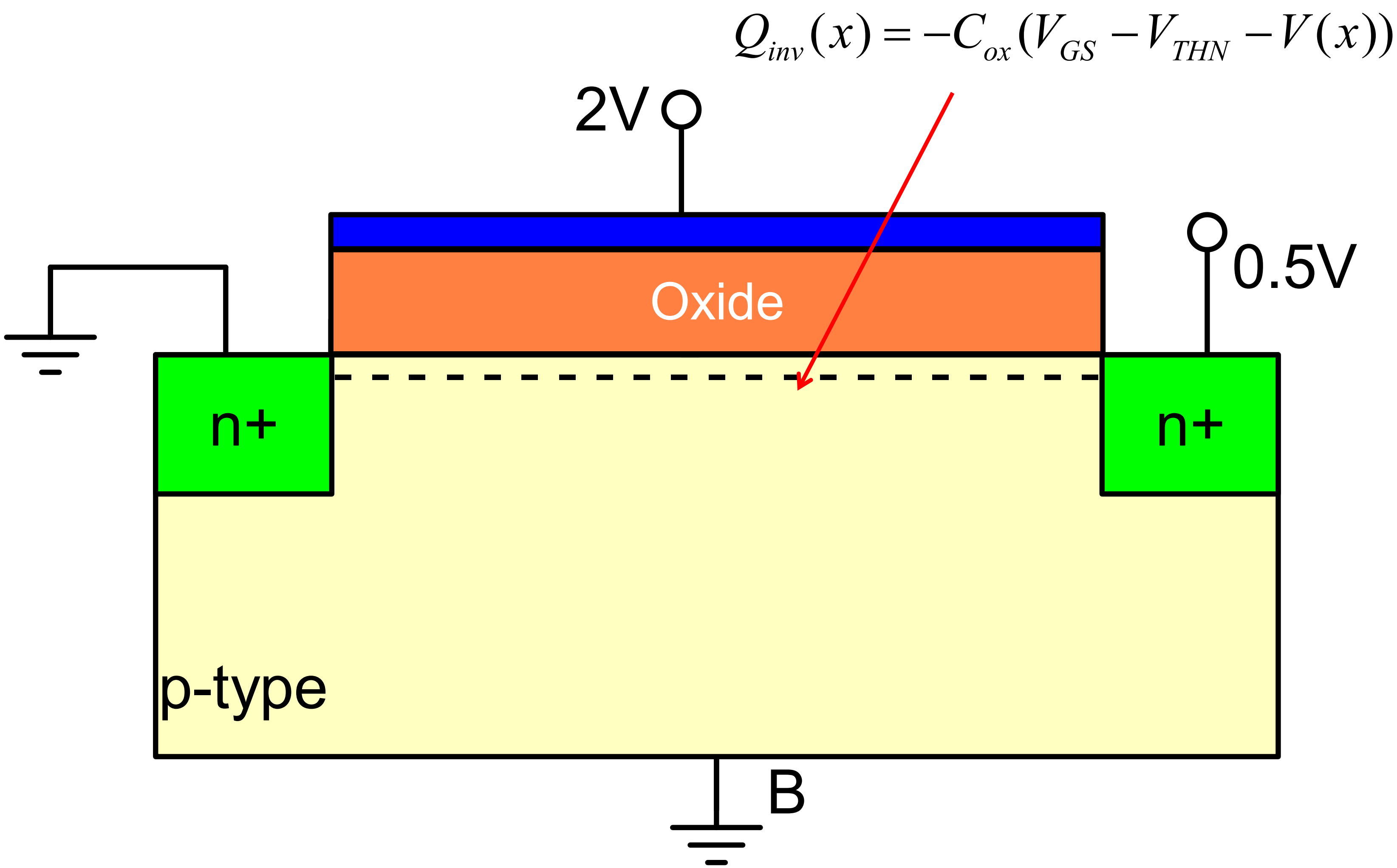


Operation of the MOSFET

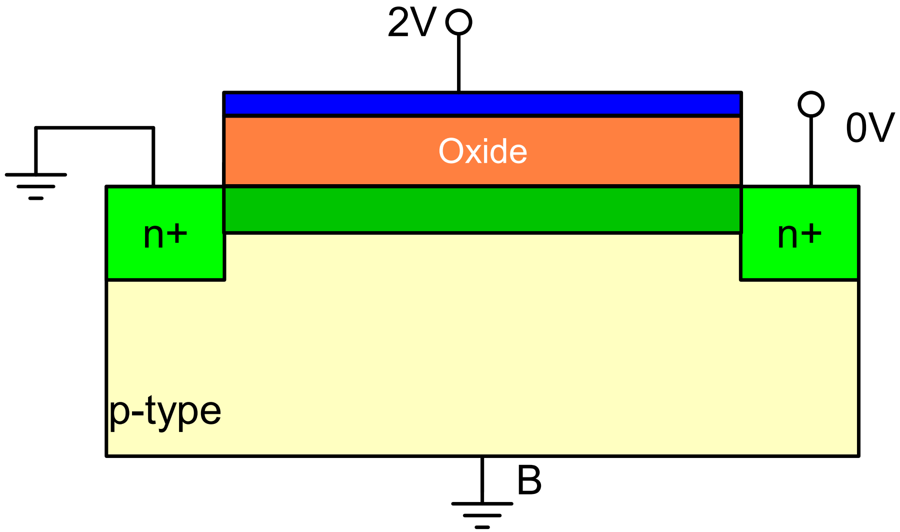


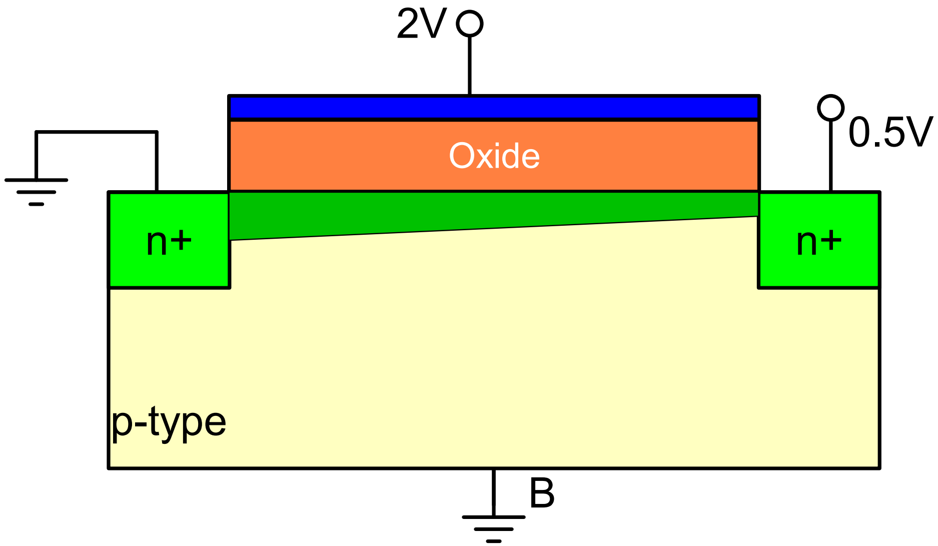
$$C'_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

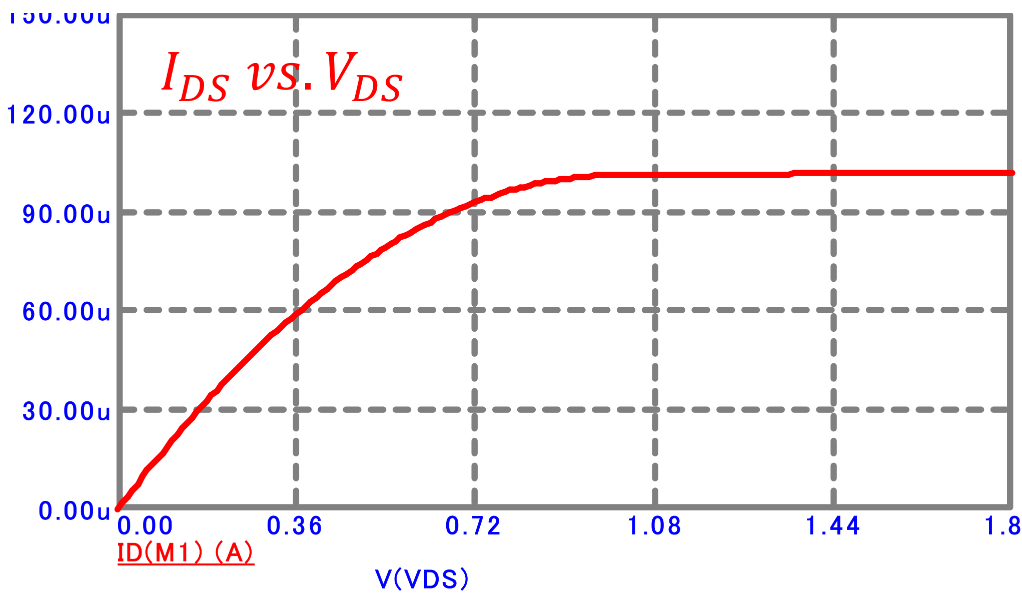
Inversion charge/area : $Q_{inv} = -C_{ox}(V_{GS} - V_{THN})$



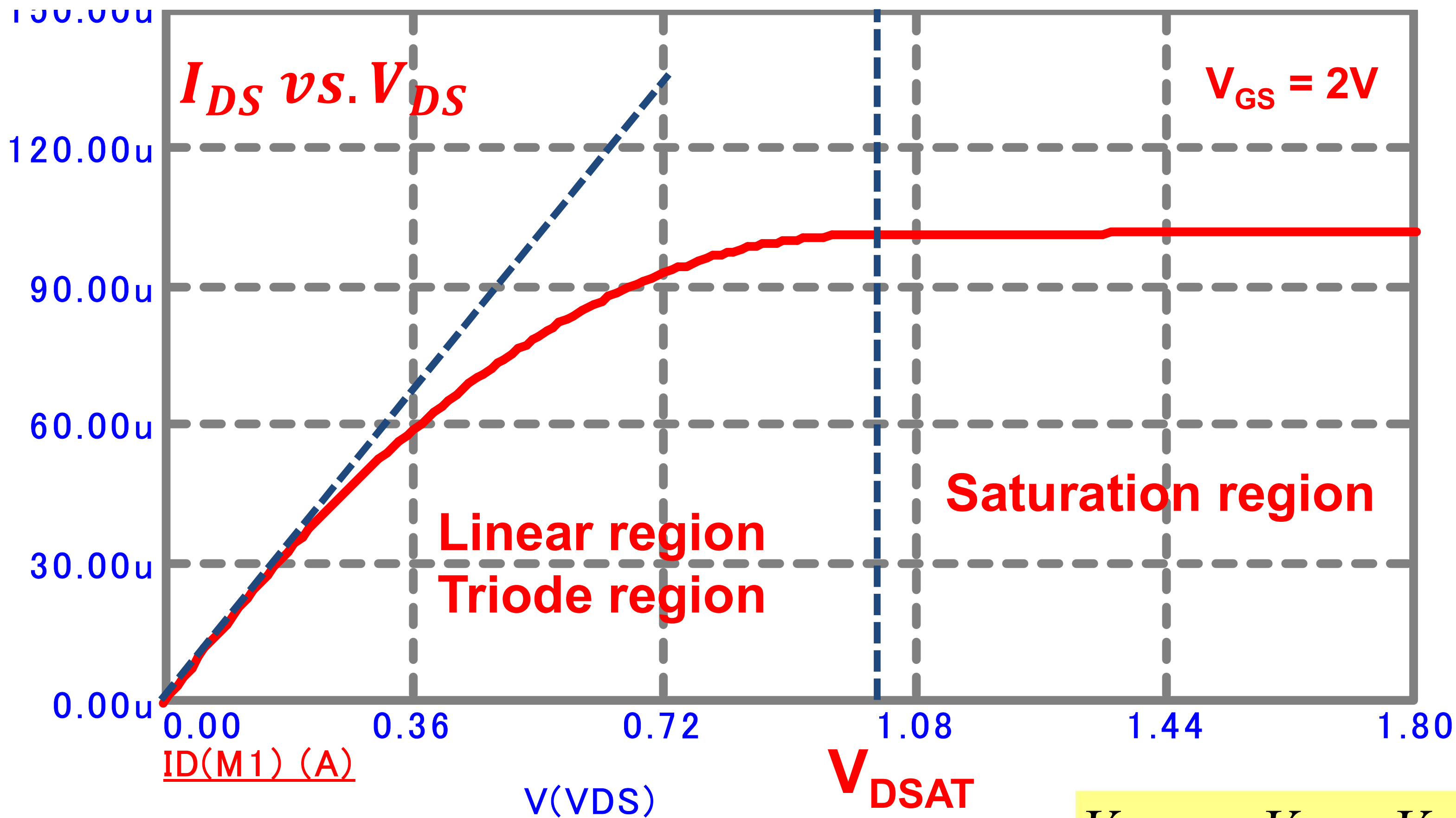
When a positive drain voltage is applied, current flows from drain to source and inversion charge density decreases from source to drain end.


2V
0V
Oxide
n+
n+
p-type
B


2V
0.5V
Oxide
n+
n+
p-type
B


I_{DS} vs. V_{DS}
120.00u
90.00u
60.00u
30.00u
0.00u
0.00
0.36
0.72
1.08
1.44
ID(M1) (A)
V(VDS)

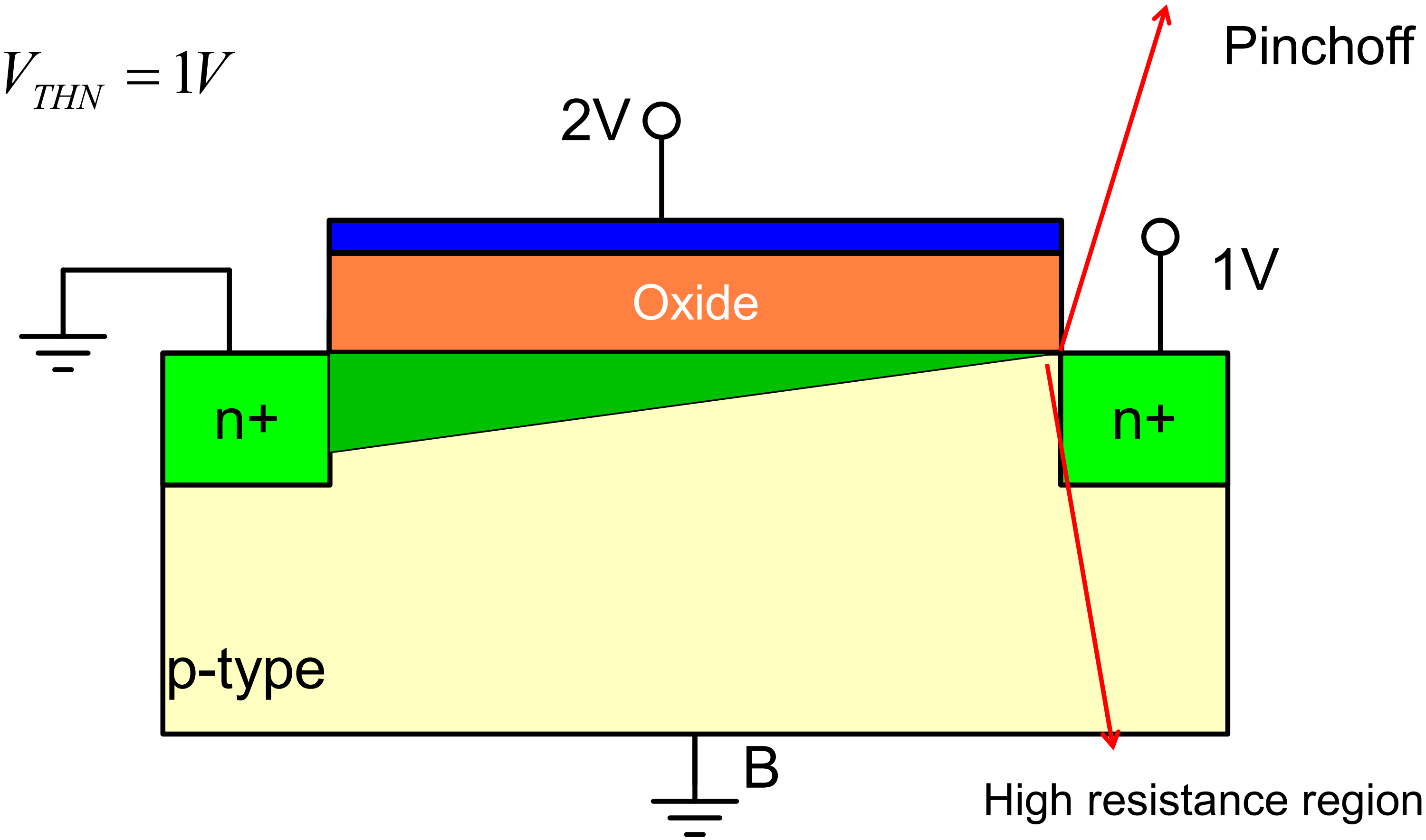
$$I_{DS} = \frac{V_{DS}}{R_{ch}} > 0$$



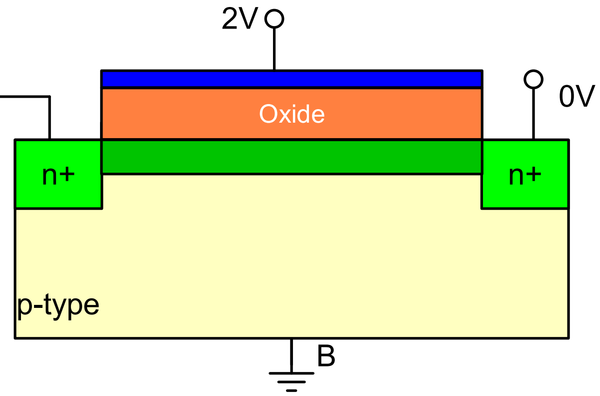
$$V_{DSAT} = V_{GS} - V_{THN}$$

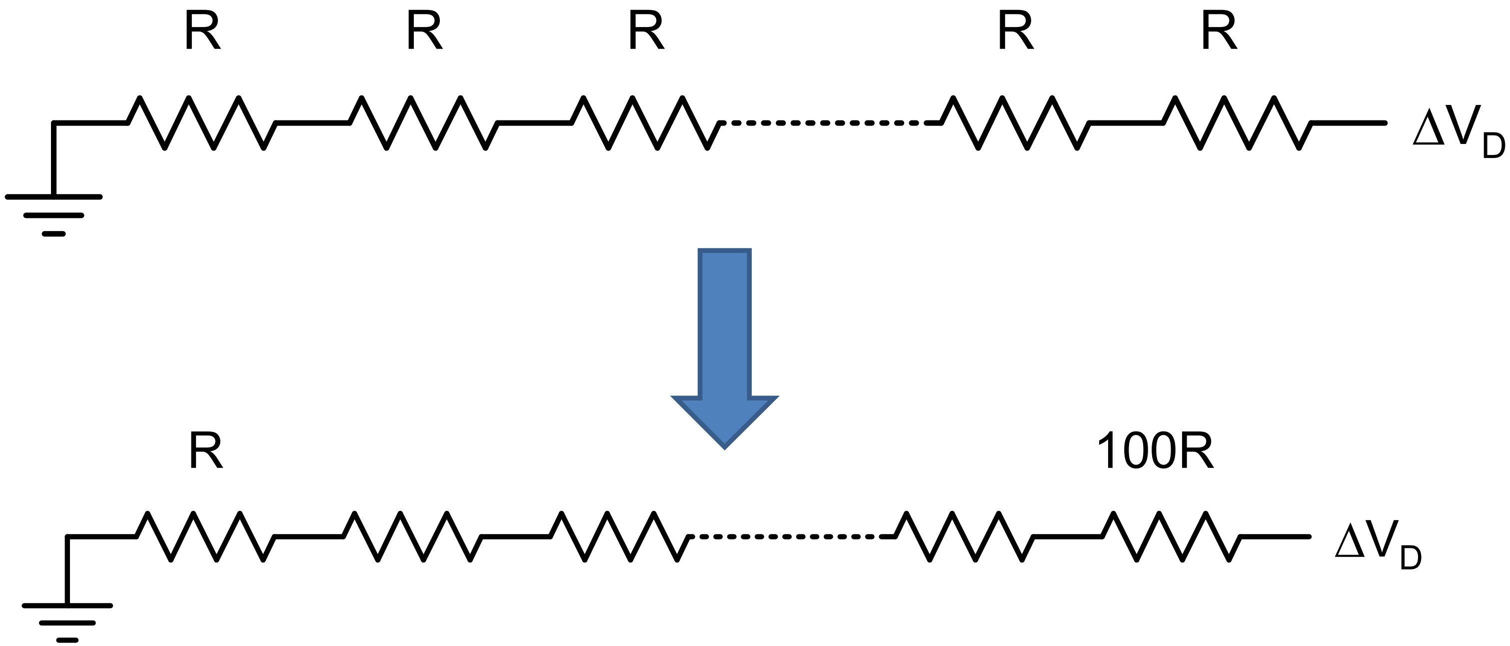
$$Q_{inv}(x) = -C_{ox}(V_{GS} - V_{THN} - V(x)) \cong -C_{ox}(2-1-1) = 0$$

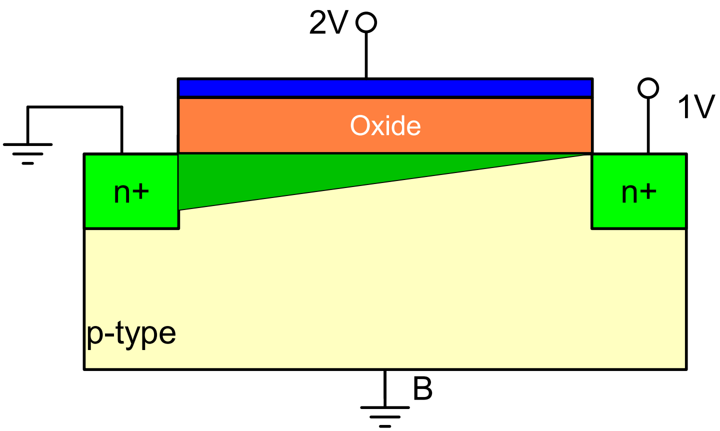
$$V_{THN} = 1V$$

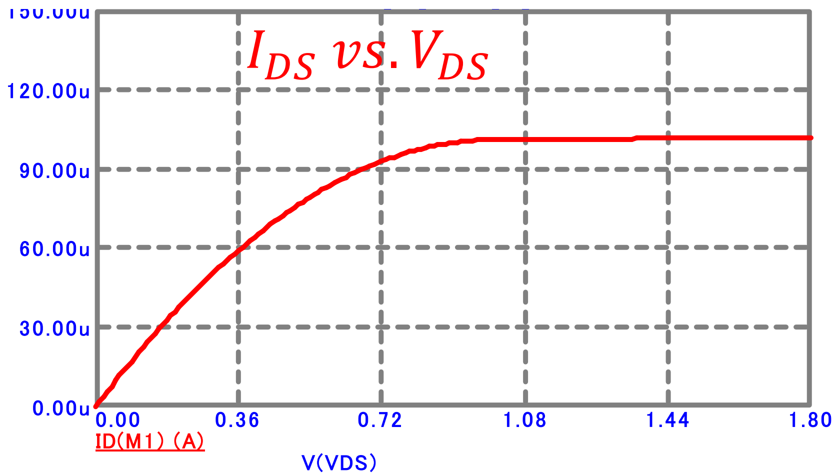


Any further increase in drain bias is absorbed in a small region next to the drain and rest of channel is not much affected and thus current becomes constant.



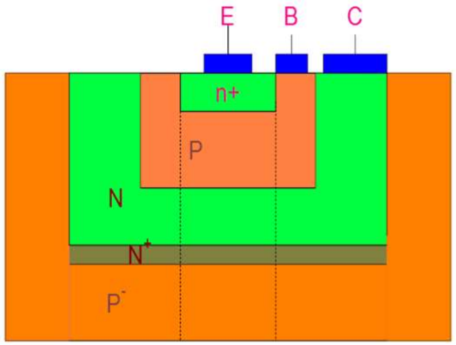




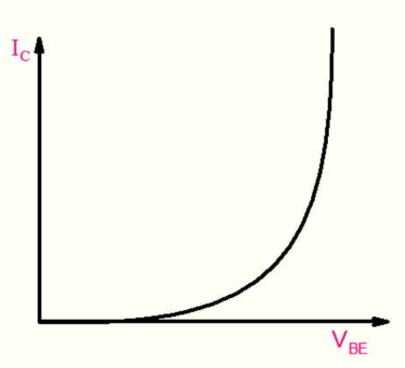


$$\frac{\partial I_{DS}}{\partial V_{GS}} >> \frac{\partial I_{DS}}{\partial V_{DS}}$$

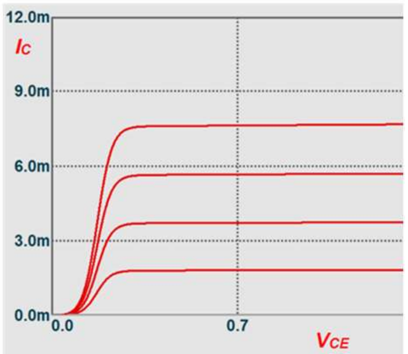
BJT



E
B
C
n+
P
N
N+
P-

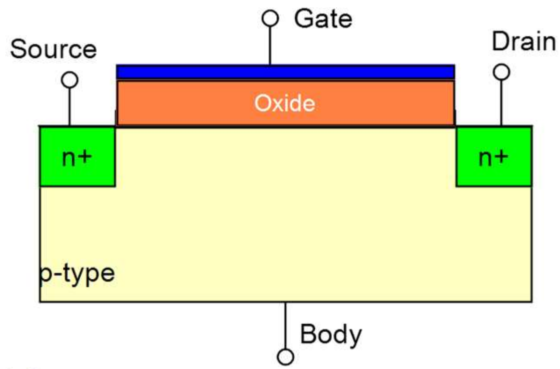


IC
VBE

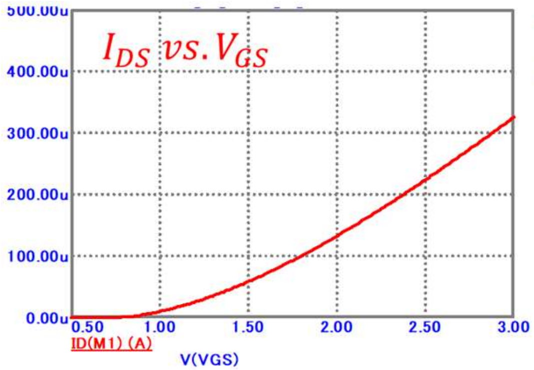


12.0m
Ic
9.0m
6.0m
3.0m
0.0m
0.0
0.7
VCE

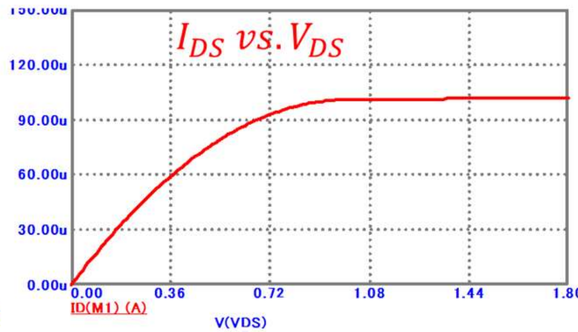
MOSFET



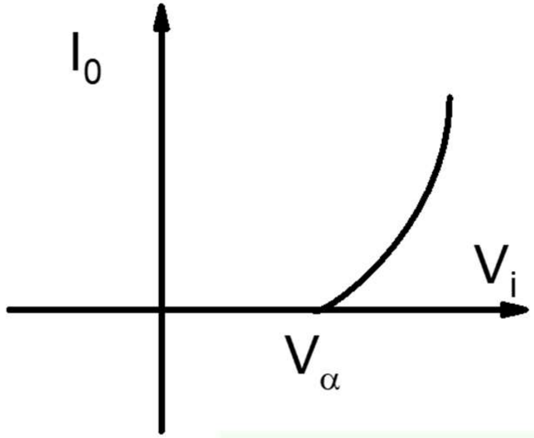
Gate
Source
Drain
Oxide
n+
n+
p-type
Body



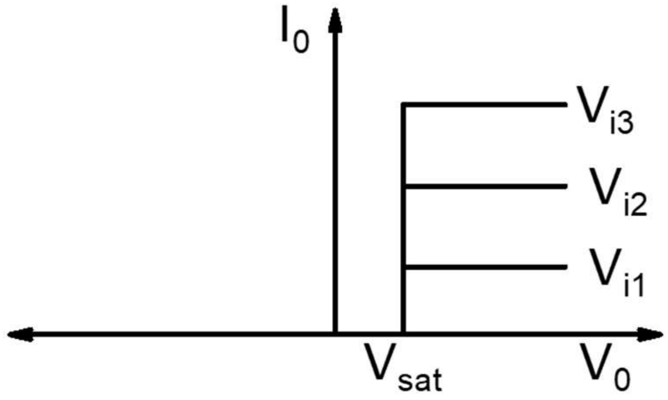
I_{DS} vs. V_{GS}
400.00u
300.00u
200.00u
100.00u
0.00u
0.50
1.00
1.50
2.00
2.50
3.00
ID(M1) (A)
V(VGS)



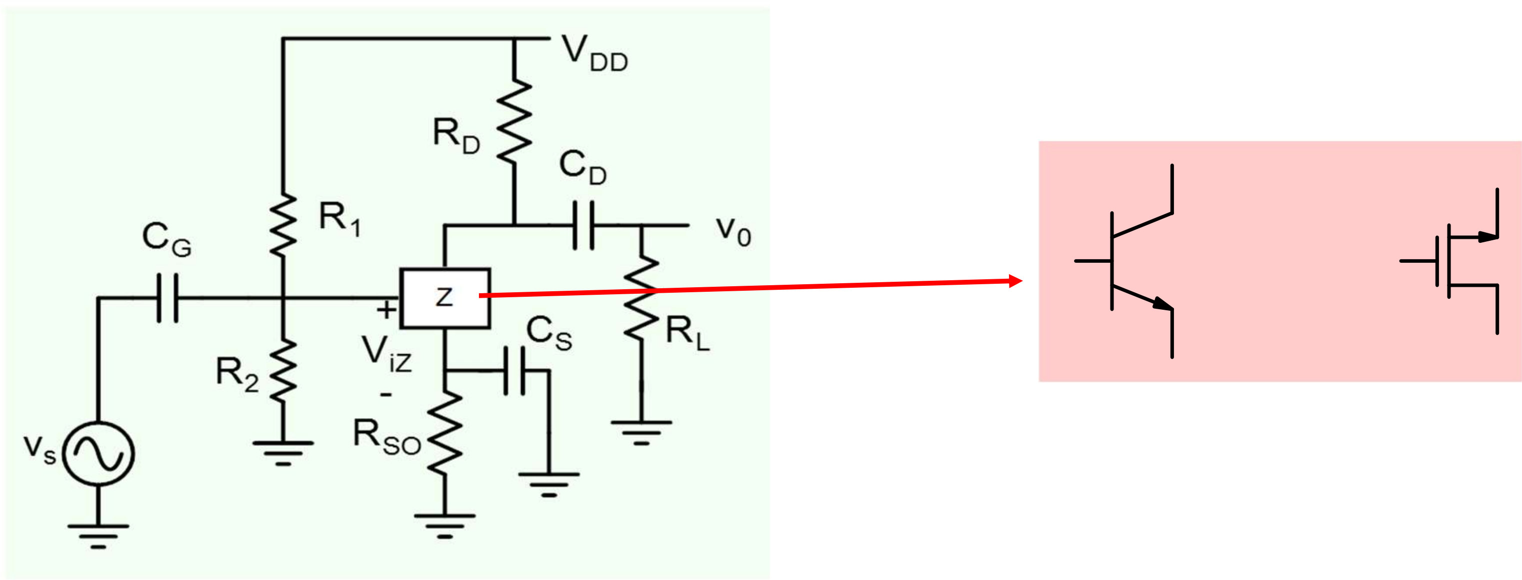
I_{DS} vs. V_{DS}
120.00u
90.00u
60.00u
30.00u
0.00u
0.00
0.36
0.72
1.08
1.44
1.80
ID(M1) (A)
V(VDS)



I_0
V_i
V_α



I_0
V_{i3}
V_{i2}
V_{i1}
V_{sat}
V_0



V_{DD}
R_D
C_D
R_1
C_G
v_0
Z
+
V_{iZ}
-
C_S
R_L
R_2
R_{SO}
v_s