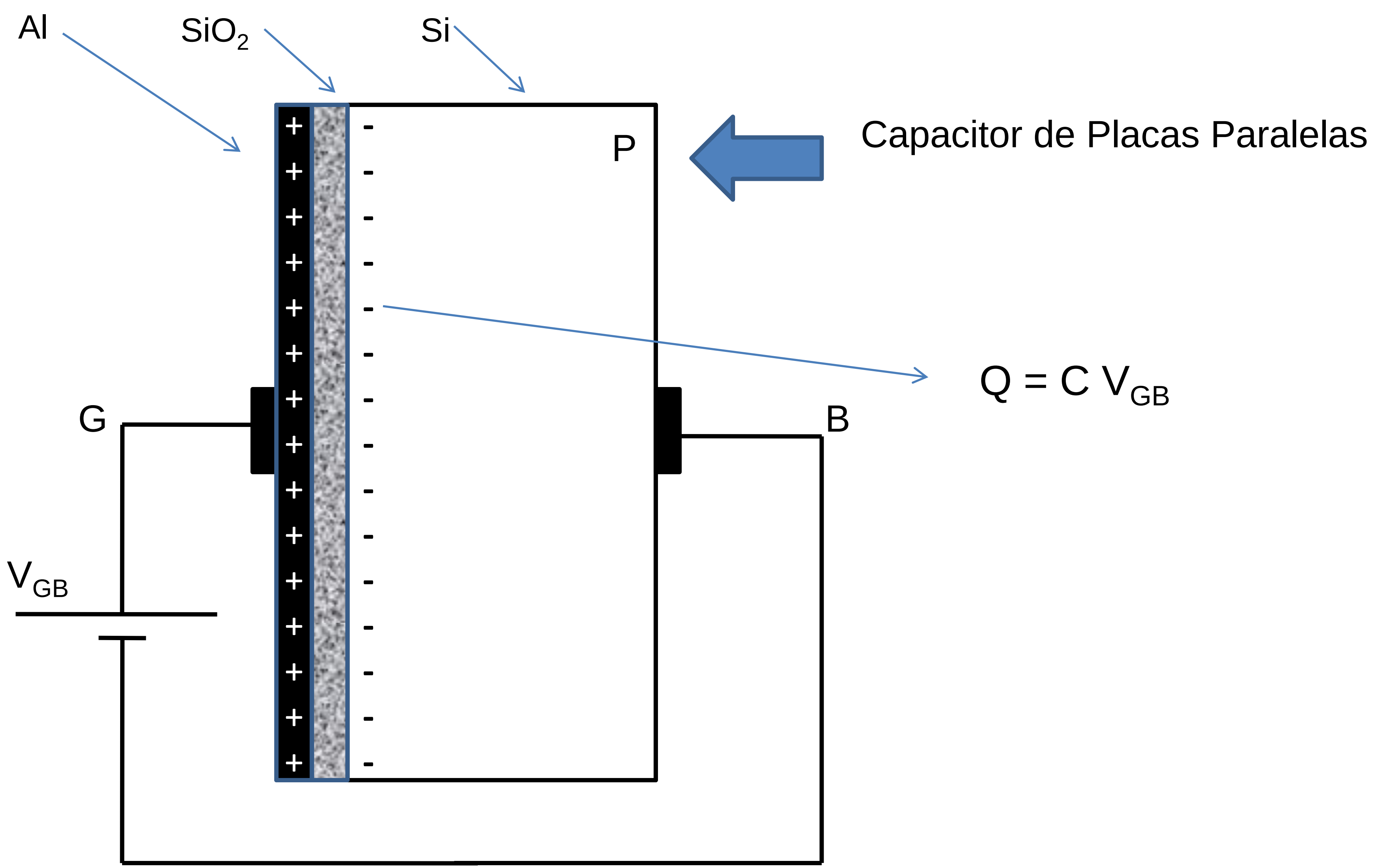
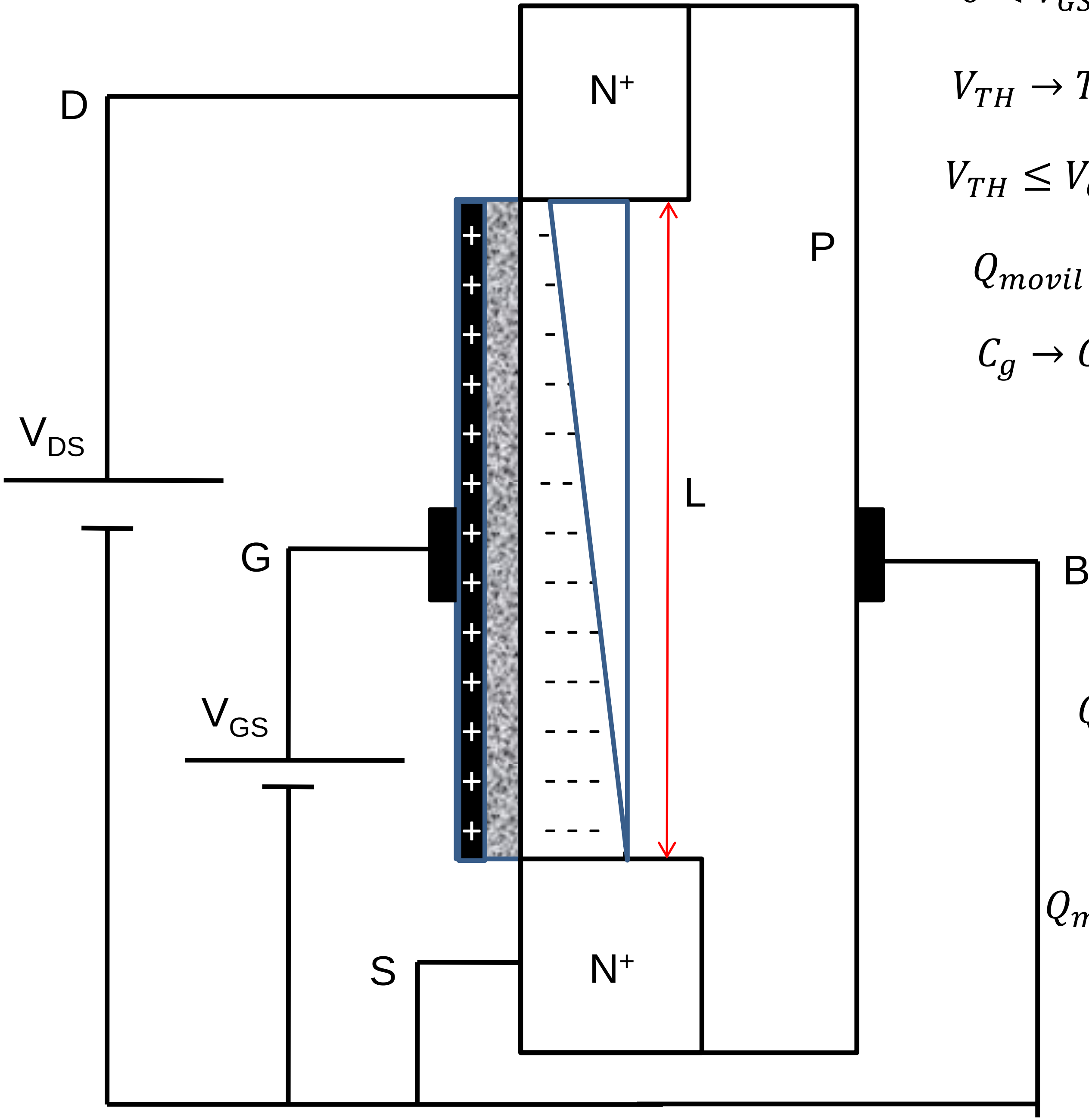
TRANSISTOR DE EFECTO DE CAMPO (FET)

METAL–OXIDO–SEMICONDUCTOR (MOSFET)





$$0 < V_{GS} < V_{TH} \rightarrow Q_{movil} = 0$$

$$V_{TH} \rightarrow Tension\ umbral$$

$$V_{TH} \leq V_{GS} \rightarrow Carga\ movil\ en\ el\ canal$$

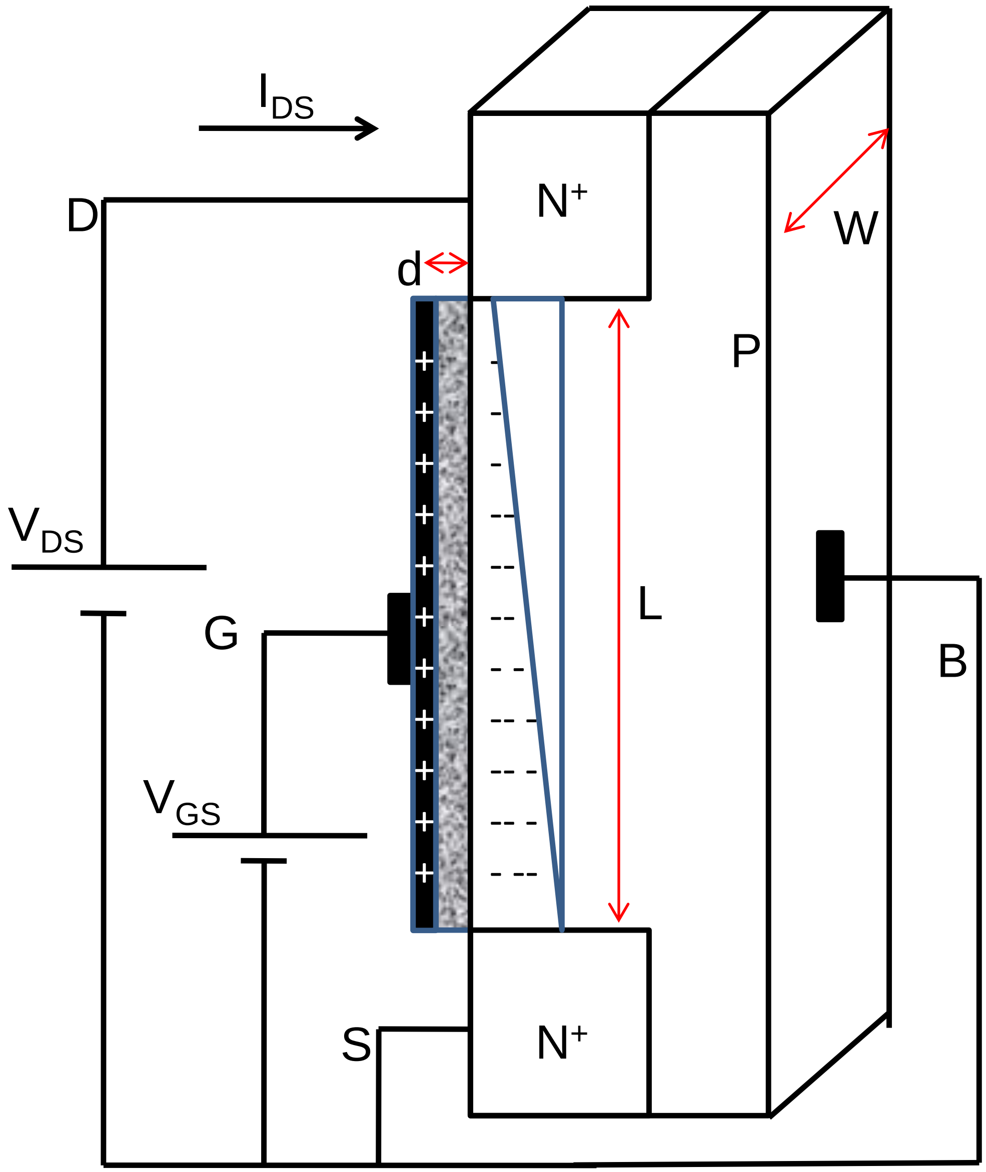
$$Q_{movil} = C_g(V_{GS} - V_{TH})$$

$$C_g \rightarrow Capacidad\ de\ compuerta$$

$$C_g = \varepsilon \frac{A}{d} = \varepsilon \frac{W\ L}{d}$$

$$Q_{movil} = C_g\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)$$

$$Q_{movil} = \varepsilon \frac{WL}{d}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)$$



$$I_{DS} = \frac{Carga\ movil\ en\ el\ canal}{Tiempo\ de\ Transito}$$

$$I_{DS} = \frac{Q_{movil}}{T_T}$$

$$Q_{movil} = \varepsilon \frac{WL}{d}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)$$

$$T_T = \frac{L}{v_d} \qquad v_d = \mu E \qquad E = \frac{V_{DS}}{L}$$

$$T_T = \frac{L^2}{\mu V_{DS}}$$

$$I_{DS} = \frac{\mu\varepsilon}{d}\frac{W}{L}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)V_{DS}$$

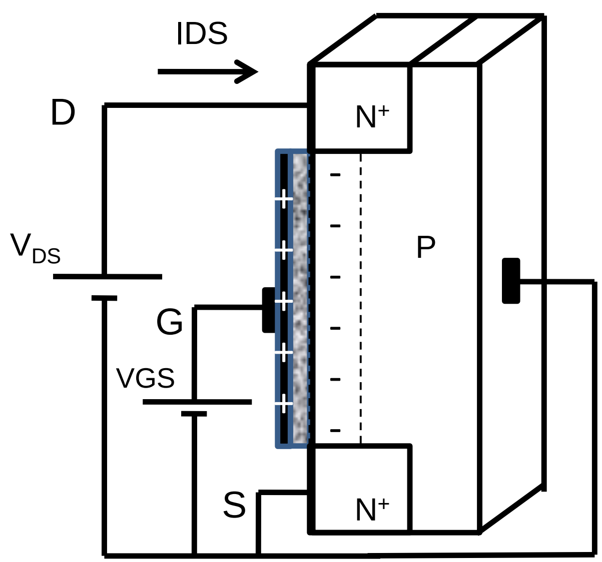
$$\frac{\mu\varepsilon}{d}\frac{W}{L} \rightarrow Depende\ de\ la\ fabricacion$$

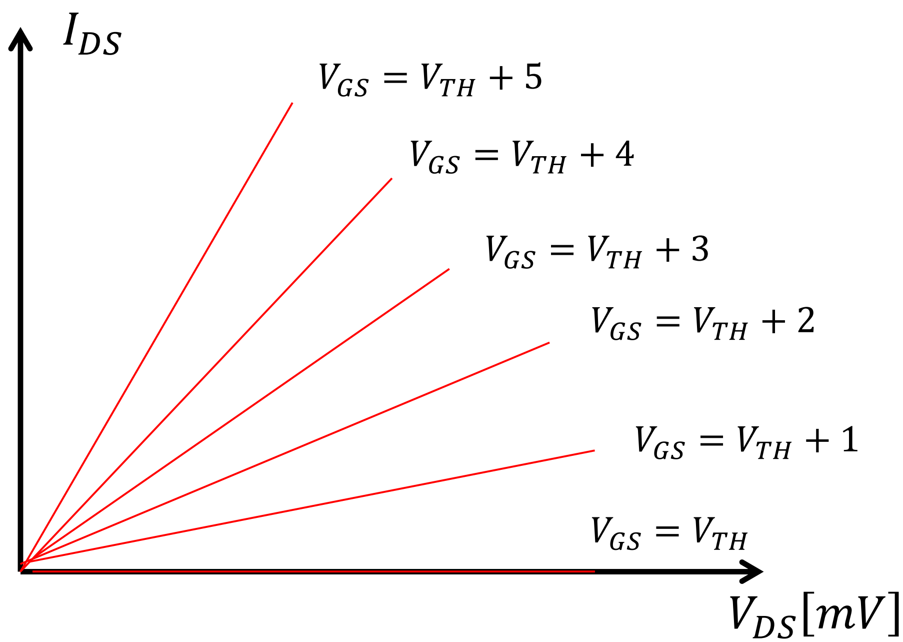
$$\beta = \frac{\mu\varepsilon}{d}\frac{W}{L}$$

$$I_{DS} = \beta(V_{GS} - V_{TH})V_{DS} - \frac{\beta}{2}V_{DS}^2$$

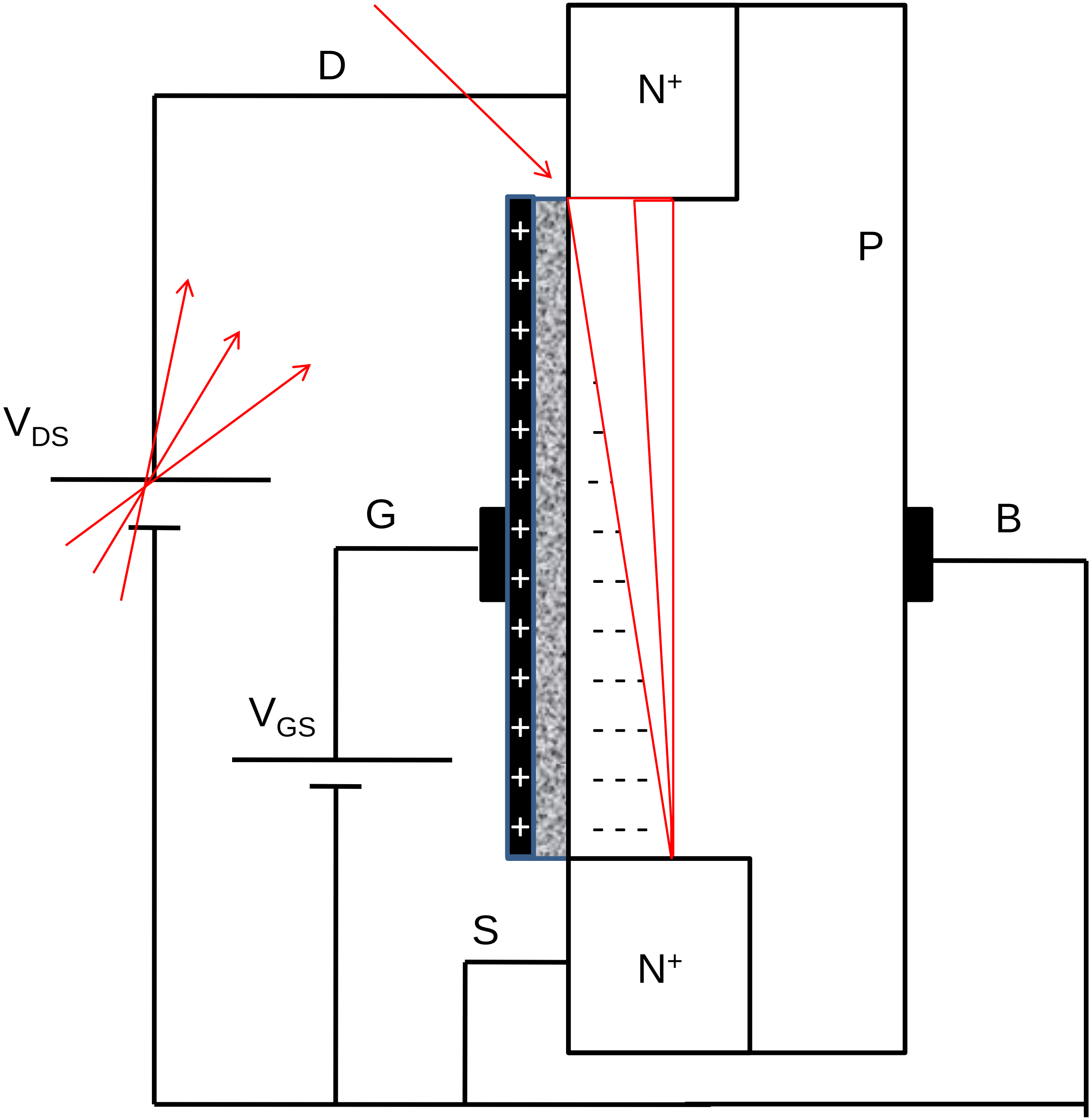
Para V_{DS} bajo $\longrightarrow$ $I_{DS} \approx \beta(V_{GS} - V_{TH})V_{DS}$

El dispositivo entre drenador y fuente se comporta como un resistor cuyo valor es controlado por V_{GS} $\longrightarrow$ $R_{DS} = \frac{V_{DS}}{I_{DS}} = \frac{1}{\beta(V_{GS} - V_{TH})}$





$V_{GS} - V_{DS} = V_{TH}$ → No hay portadores



↓

SATURACION

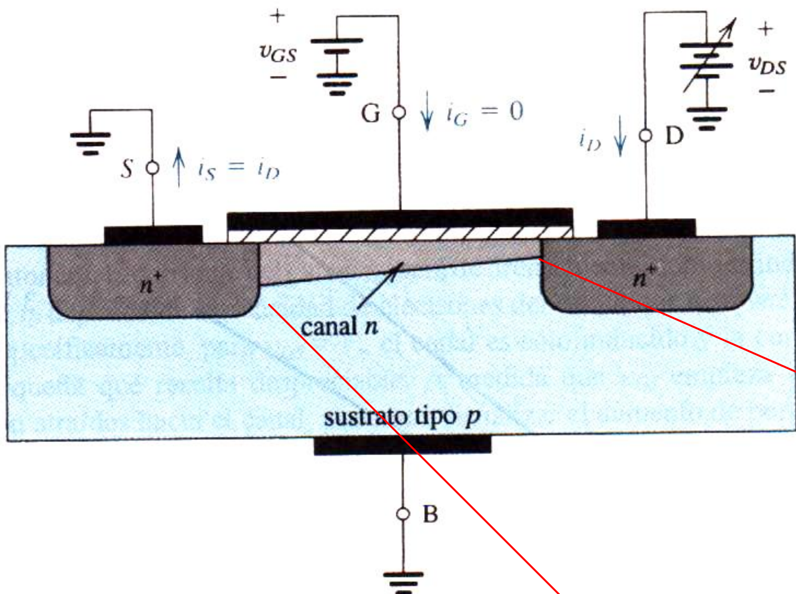
↓

I_{DS} = cte. y no depende de V_{DS}

↓

$$I_{DS} = \frac{\beta}{2}(V_{GS} - V_{TH})^2$$

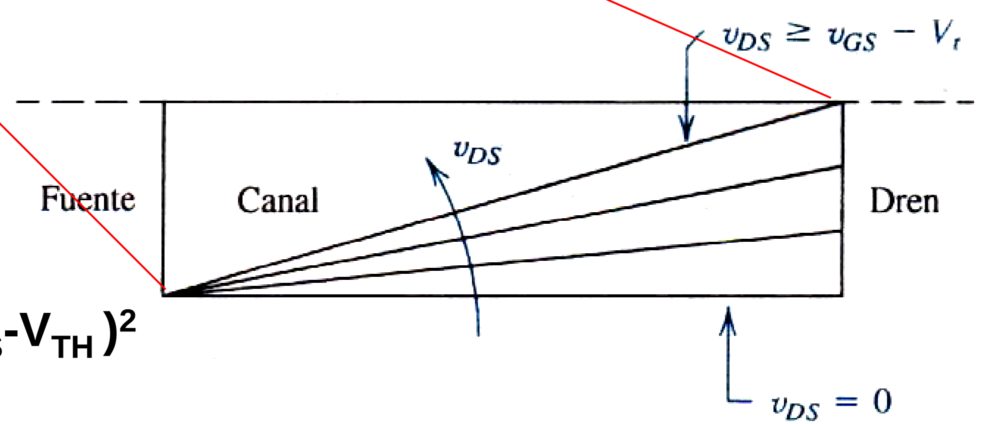
SATURACION



$$I_{DS} = \beta\,(V_{GS}-V_{TH})\,V_{DS} - \frac{\beta}{2}V^2_{DS}$$

$$(V_{GS} - V_{DS}) < V_{TH}$$

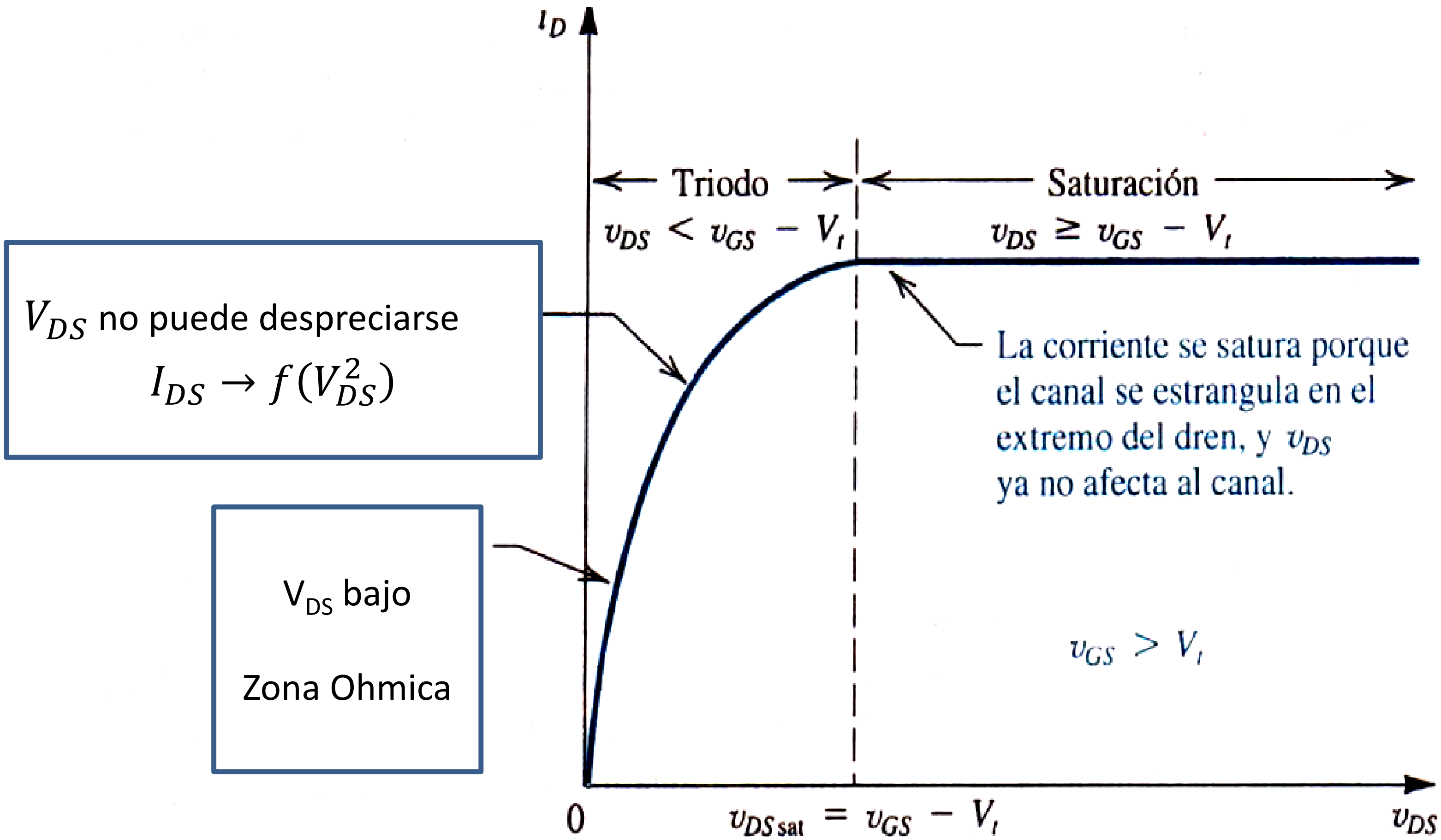
$$V_{DS} = (V_{GS} - V_{TH})$$



$$I_{DS} = \beta\,(V_{GS}-V_{TH})\,(V_{GS}-V_{TH}) - \frac{\beta}{2}(V_{GS}-V_{TH})^2$$

$$I_{DS} = \frac{\beta}{2}(V_{GS}-V_{TH})^2$$

$$\boldsymbol{I_{DS} = \beta(V_{GS} - V_{TH})V_{DS} - \frac{\beta}{2}V_{DS}^2}$$



ZONAS DE OPERACION

Corte $\Rightarrow$ $V_{GS} < V_{TH}$ $\Rightarrow$ $I_{DS} = 0$

Ohmica

$V_{GS} \geq V_{TH}$

$V_{GS} - V_{DS} \geq V_{TH}$

$\Rightarrow$ $I_{DS} = \beta(V_{GS} - V_{TH})V_{DS} - \frac{\beta}{2}V_{DS}^2$

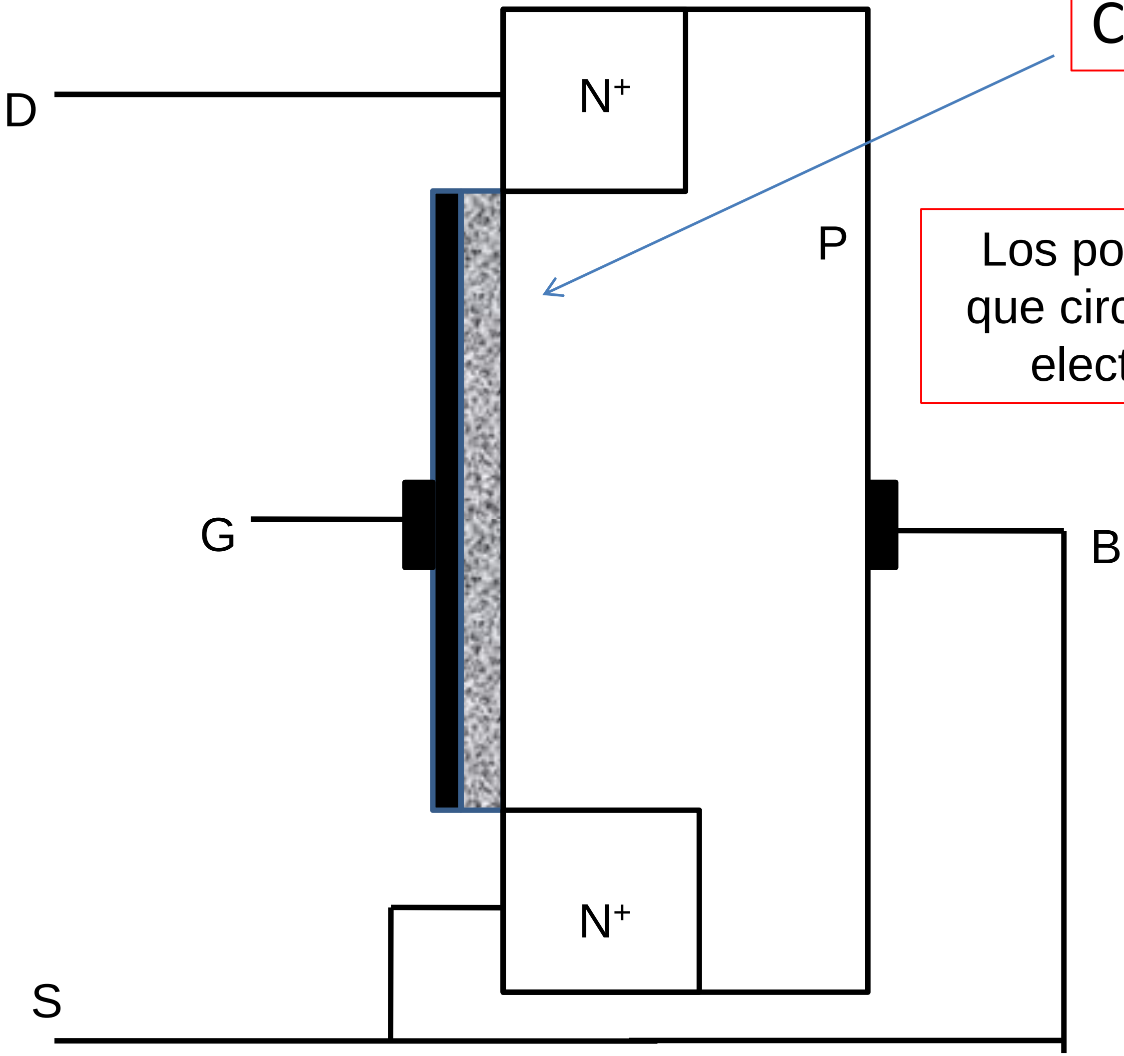
Saturación

$V_{GS} \geq V_{TH}$

$V_{GS} - V_{DS} \leq V_{TH}$

$\Rightarrow$ $I_{DS} = \frac{\beta}{2}(V_{GS} - V_{TH})^2$

MOS FET Canal N
Enriquecimiento



Canal N

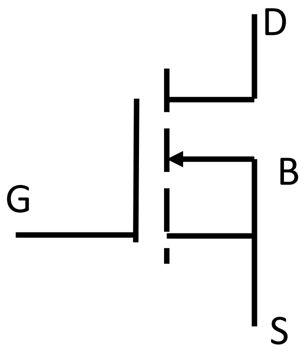
Los portadores que circulan son electrones

Enriquecimiento

Sin tension V_{GS} no hay canal

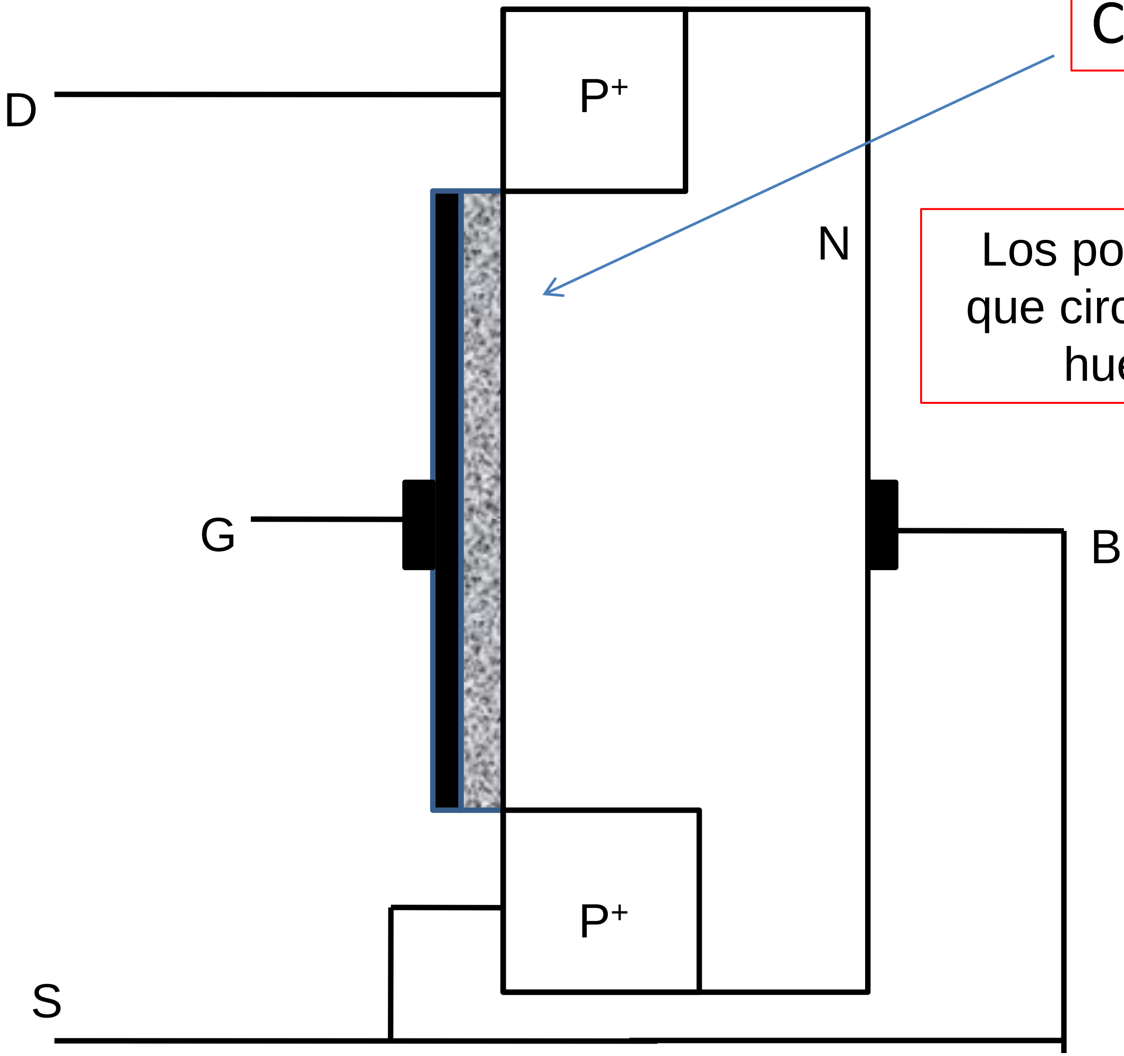
$$V_{GS} \geq 0$$

$$V_{DS} \geq 0$$



Símbolo

MOS FET Canal P
Enriquecimiento



Canal P

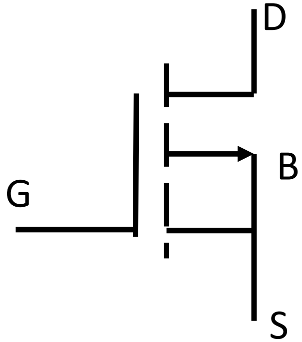
Los portadores que circulan son huecos

Enriquecimiento

Sin tensión V_{GS} no hay canal

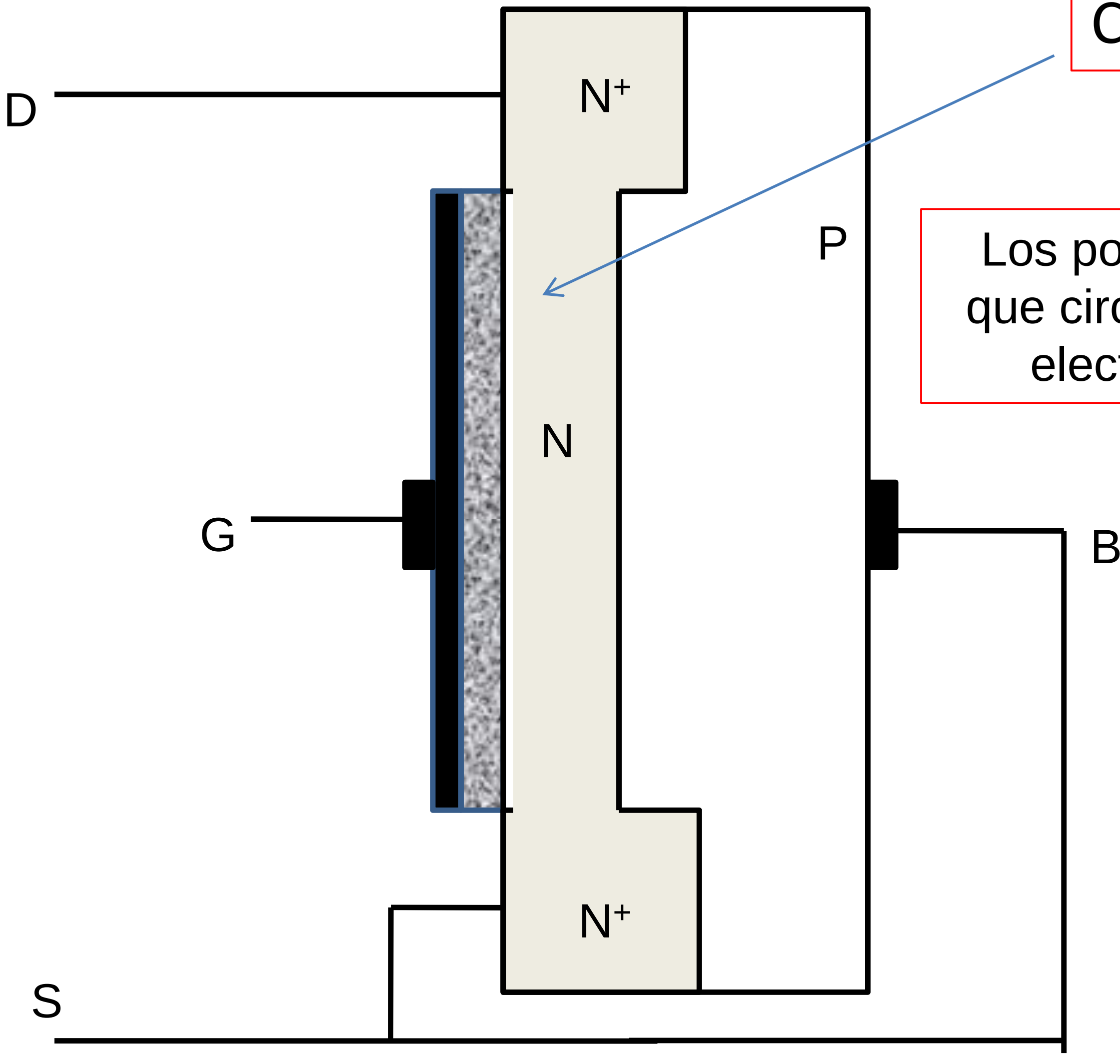
$V_{GS} \leq 0$

$V_{DS} \leq 0$



Símbolo

MOS FET Canal N
Deplexion



Canal N

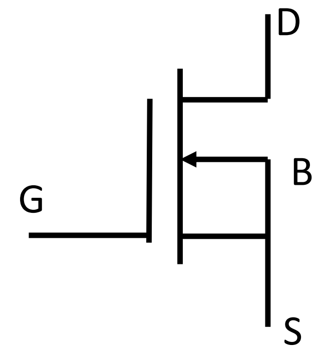
Los portadores que circulan son electrones

Deplexion

Sin tension V_{GS} hay canal

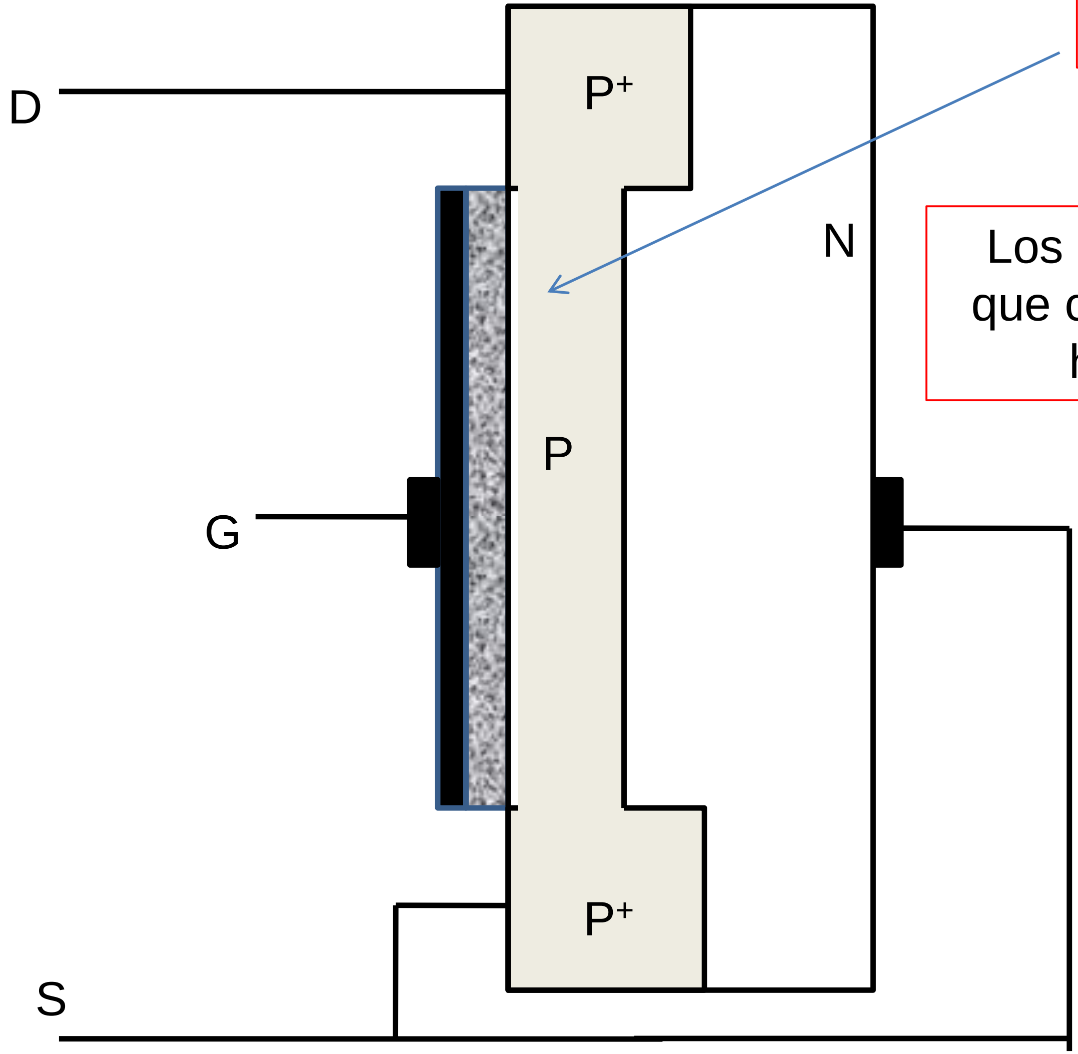
$V_{GS} \lesseqgtr 0$

$V_{DS} \geq 0$



Símbolo

MOS FET Canal P
Deplexion

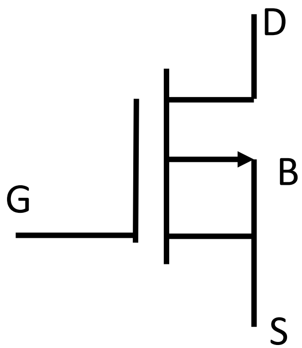


Canal P → Los portadores que circulan son huecos

Deplexion → Sin tension V_{GS} hay canal

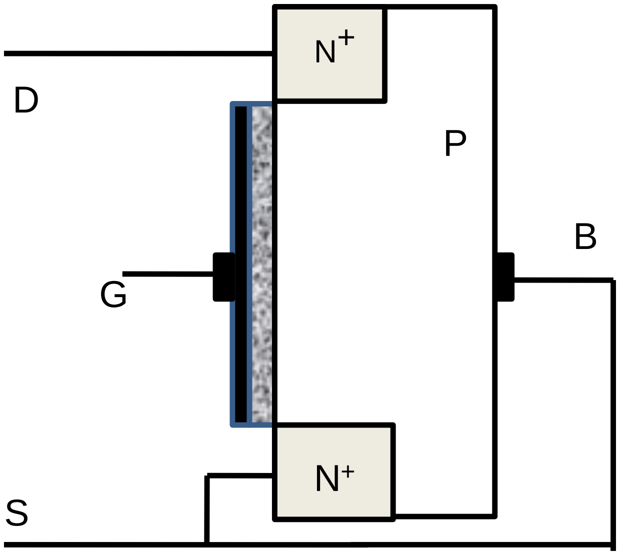
$V_{GS} \lesseqgtr 0$

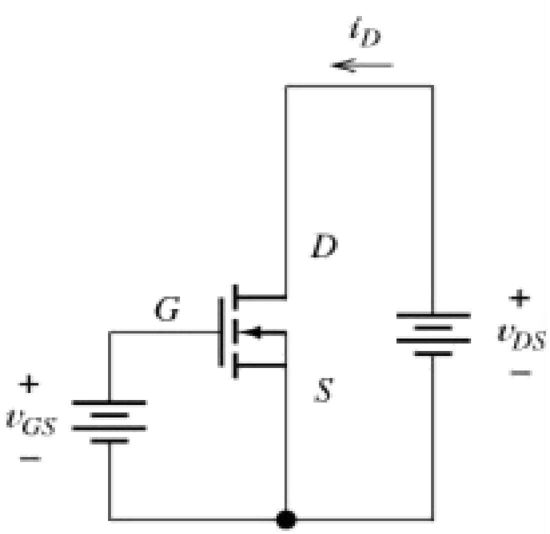
$V_{DS} \leq 0$



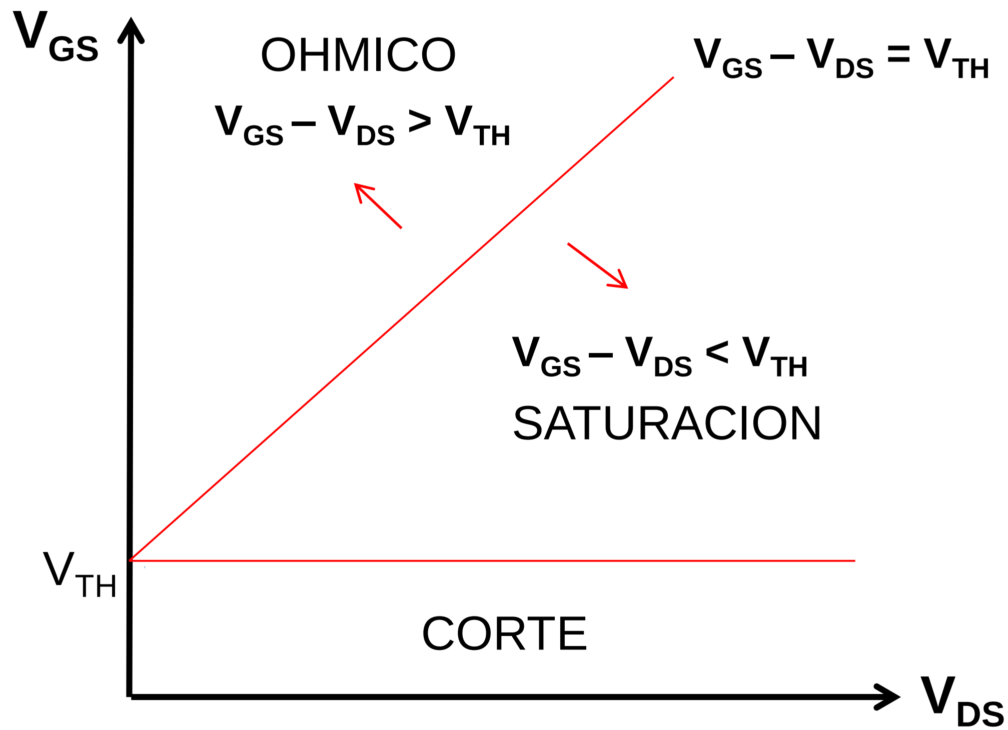
Símbolo

MOS FET Canal N Enriquecimiento

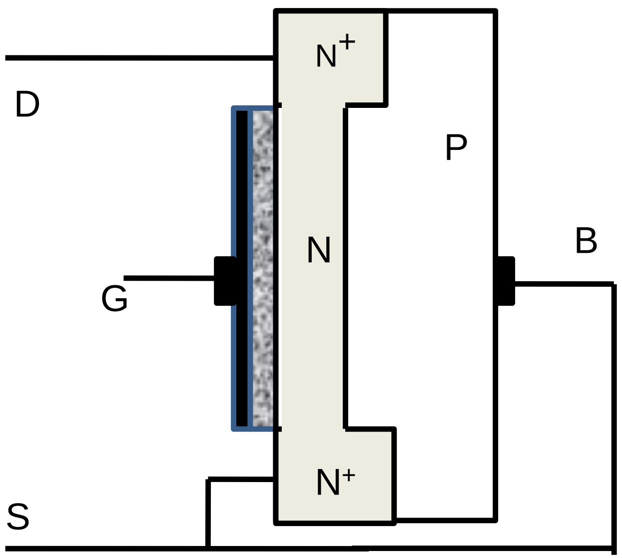


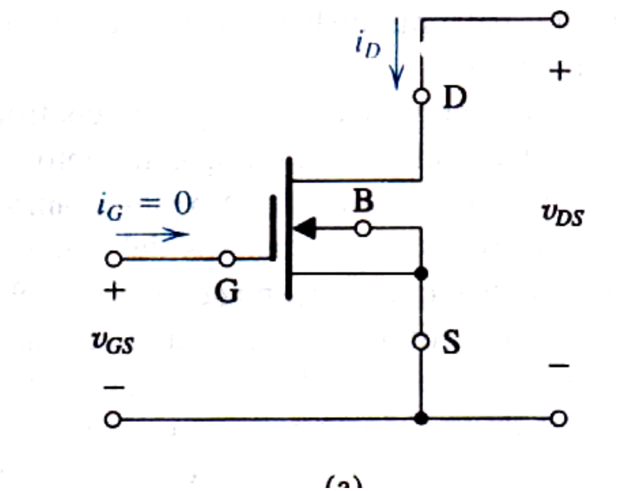


VGS vs VDS

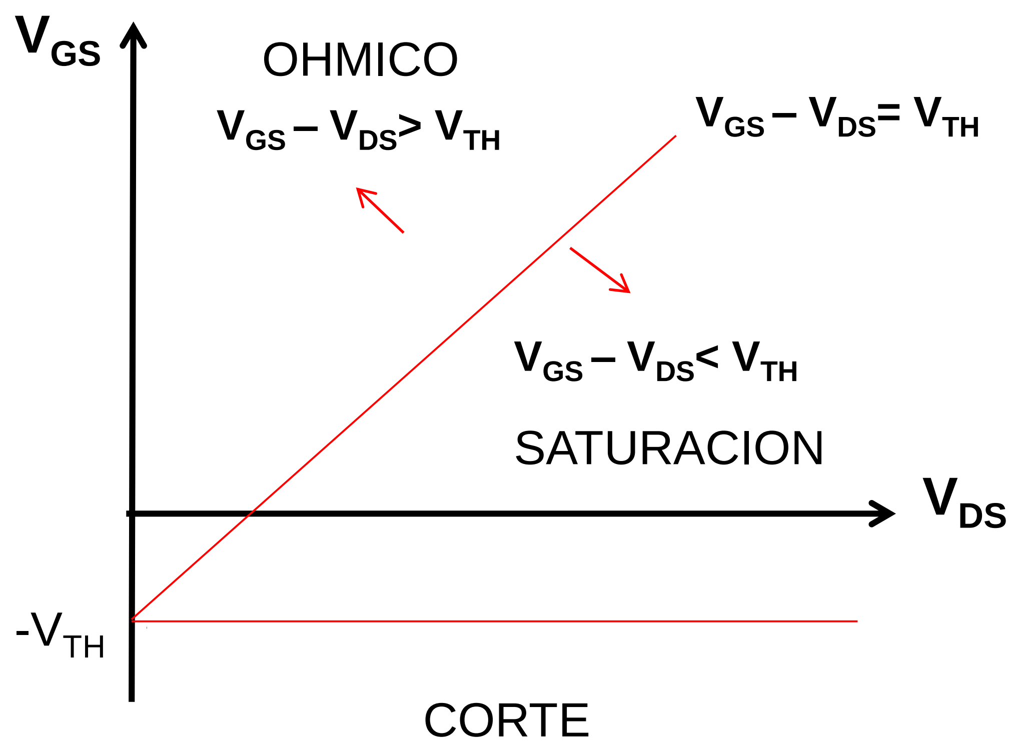


MOS FET Canal N Deplexion

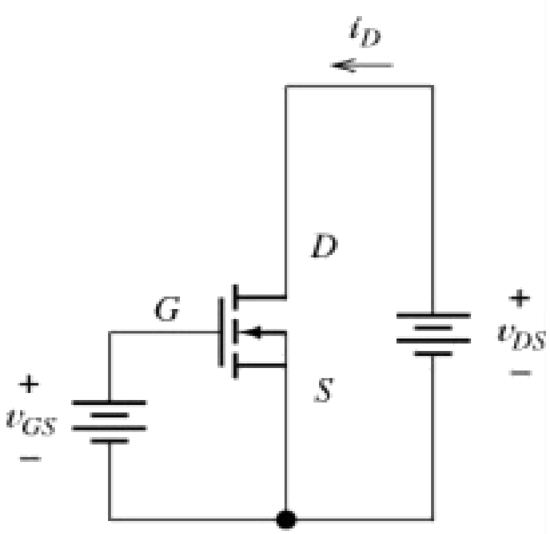


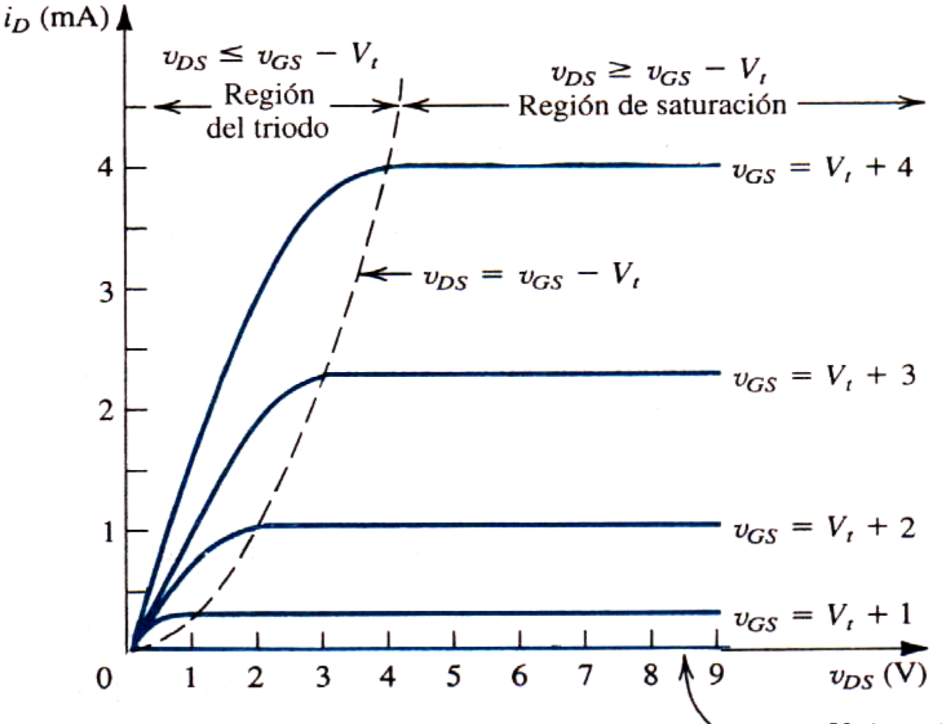


VGS vs VDS



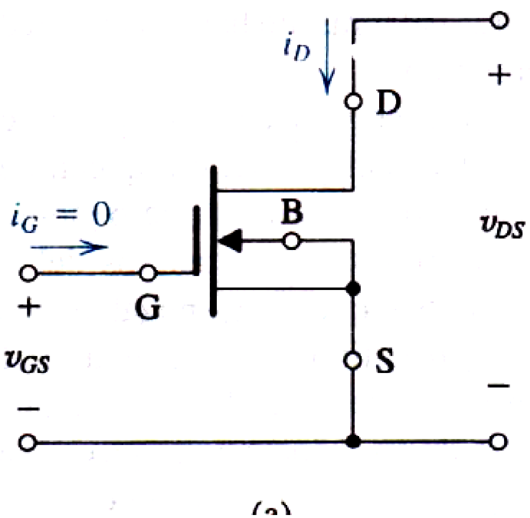
Característica V-I MOS de Enriquecimiento

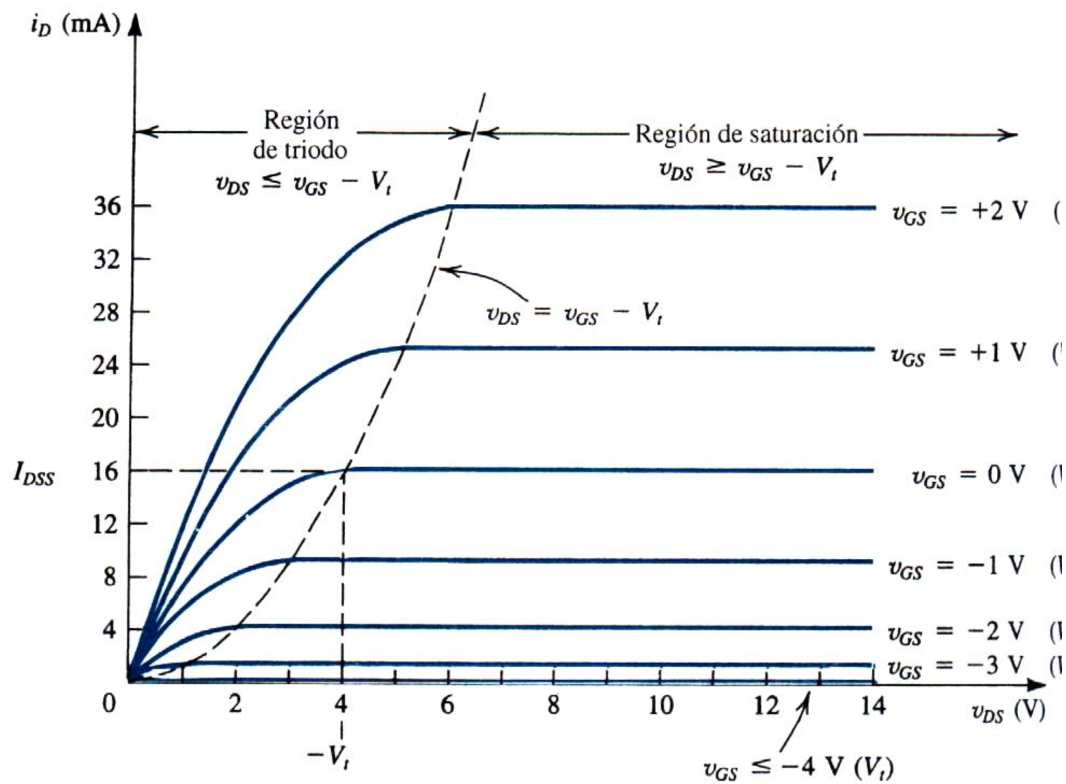


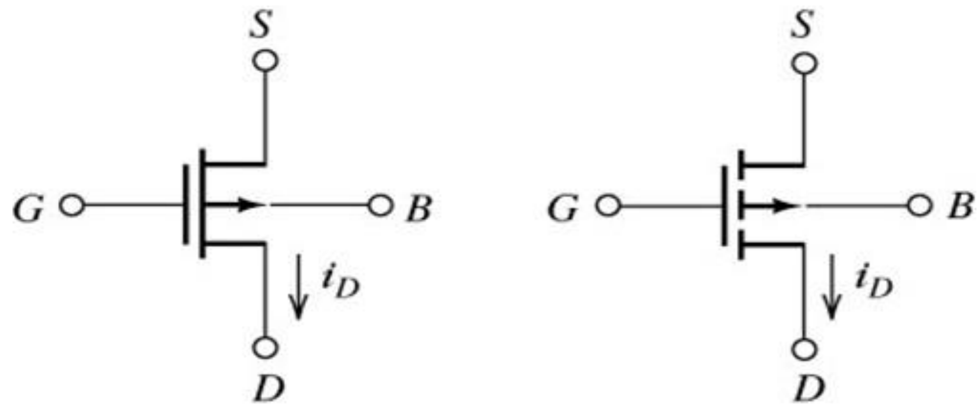


(b)

Característica V-I MOS de Deplexión

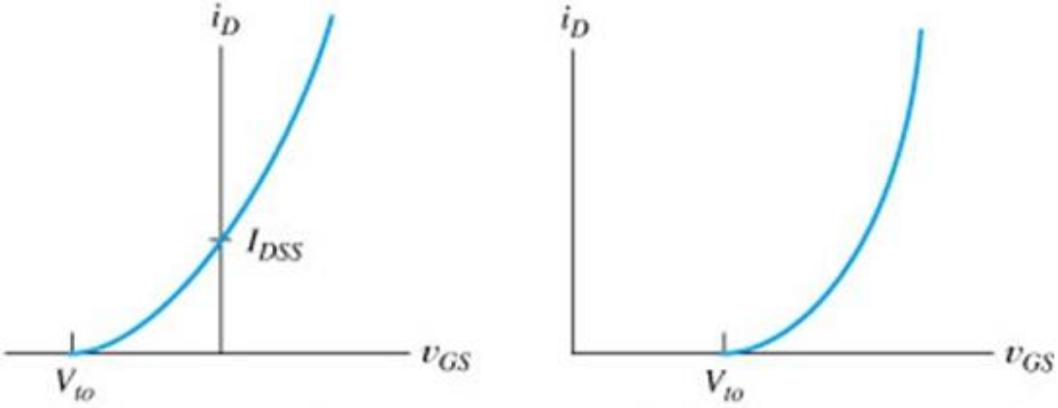






(b) Depletion MOSFET

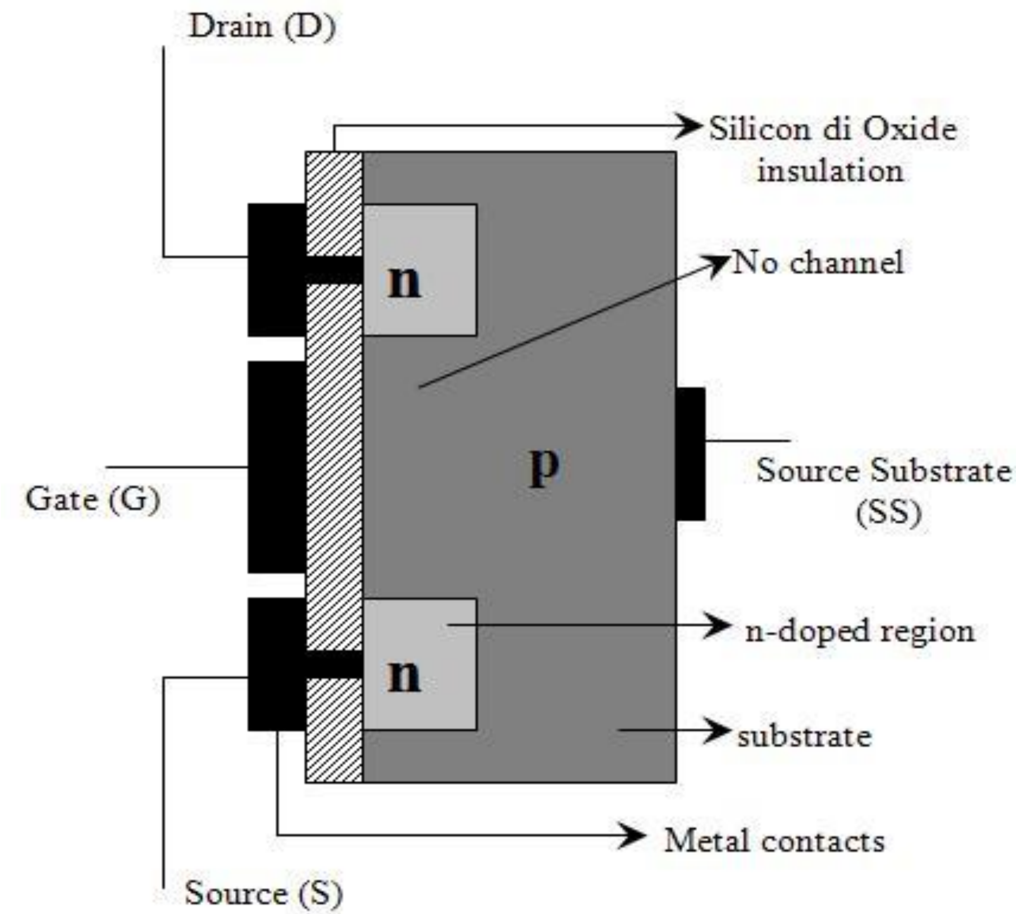
(c) Enhancement MOSFET



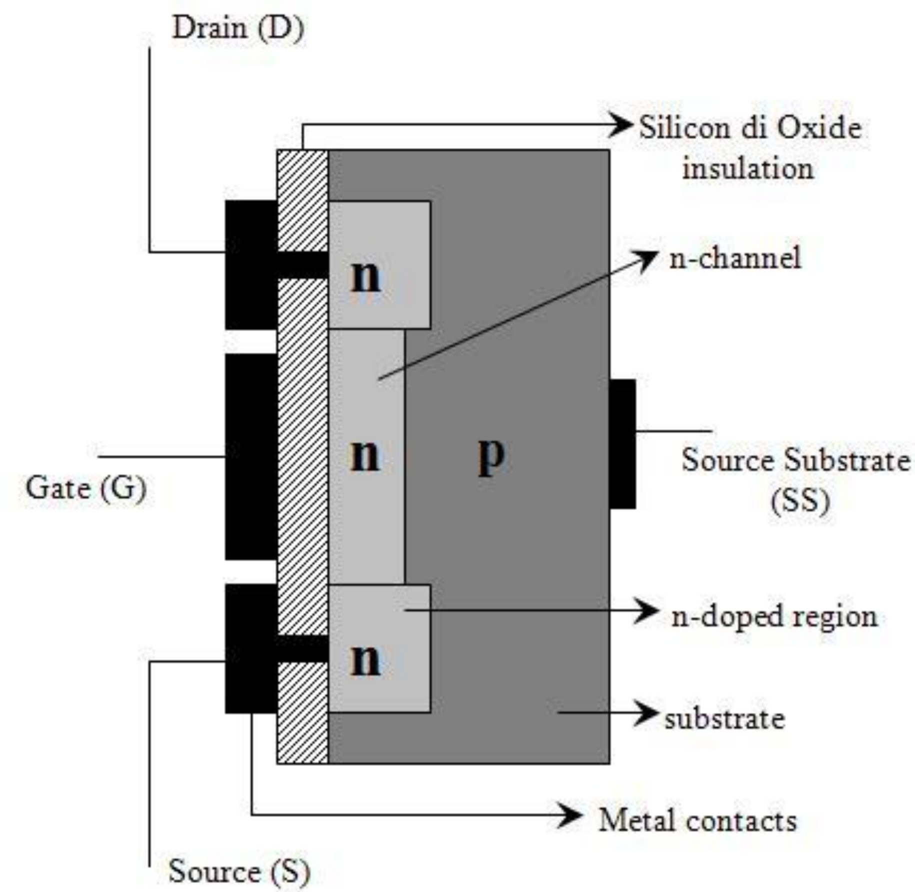
(b) Depletion MOSFET

(c) Enhancement MOSFET

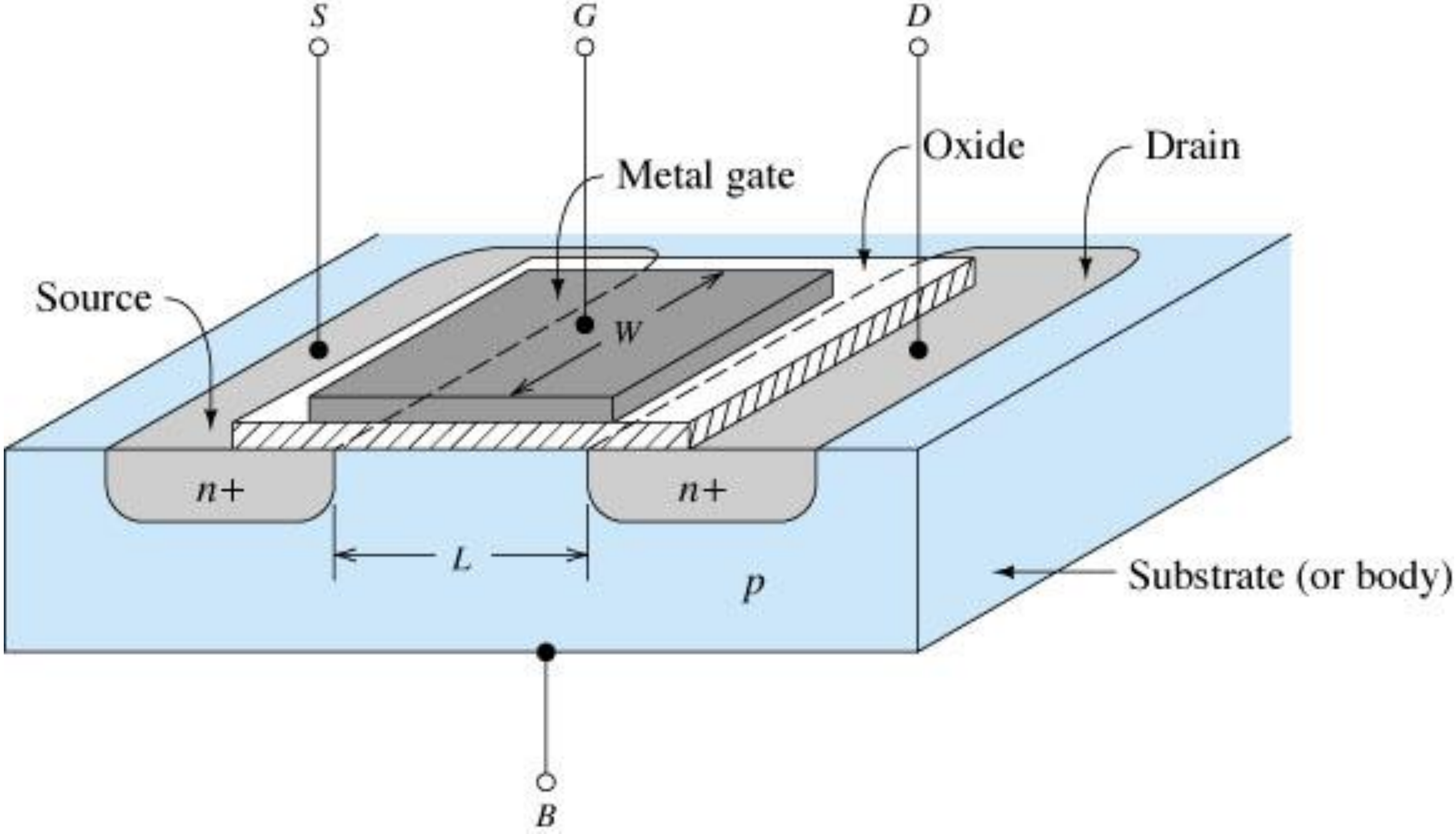
MOS de Enriquecimiento

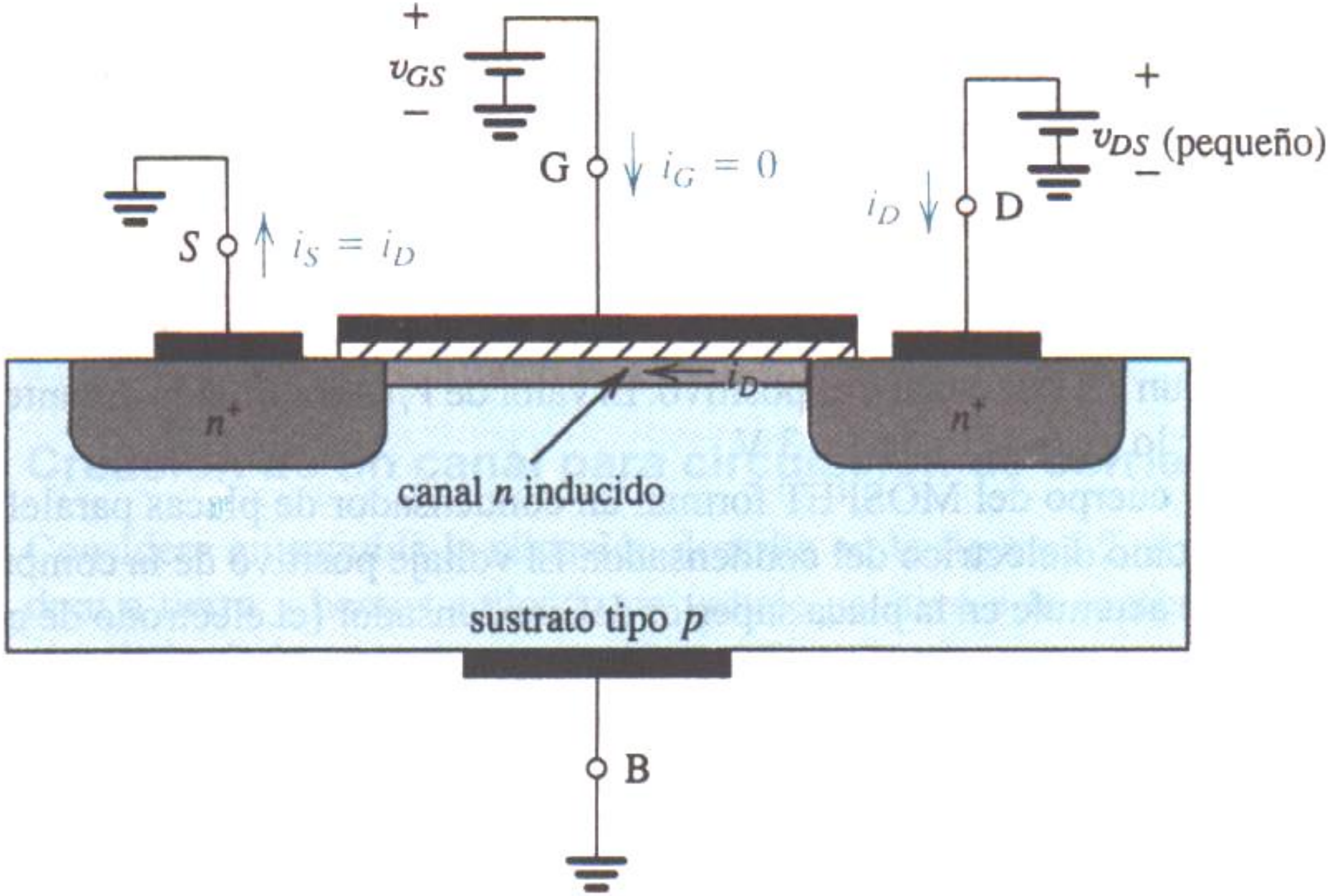


MOS de Deplexión



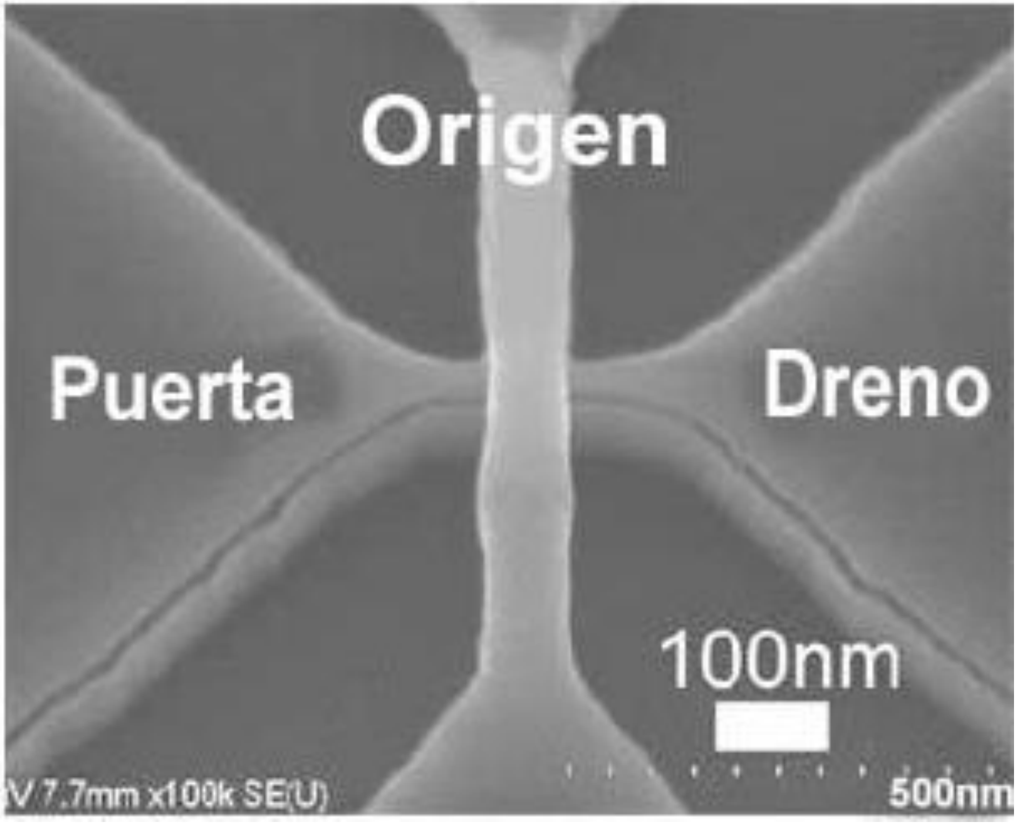
Estructura Física



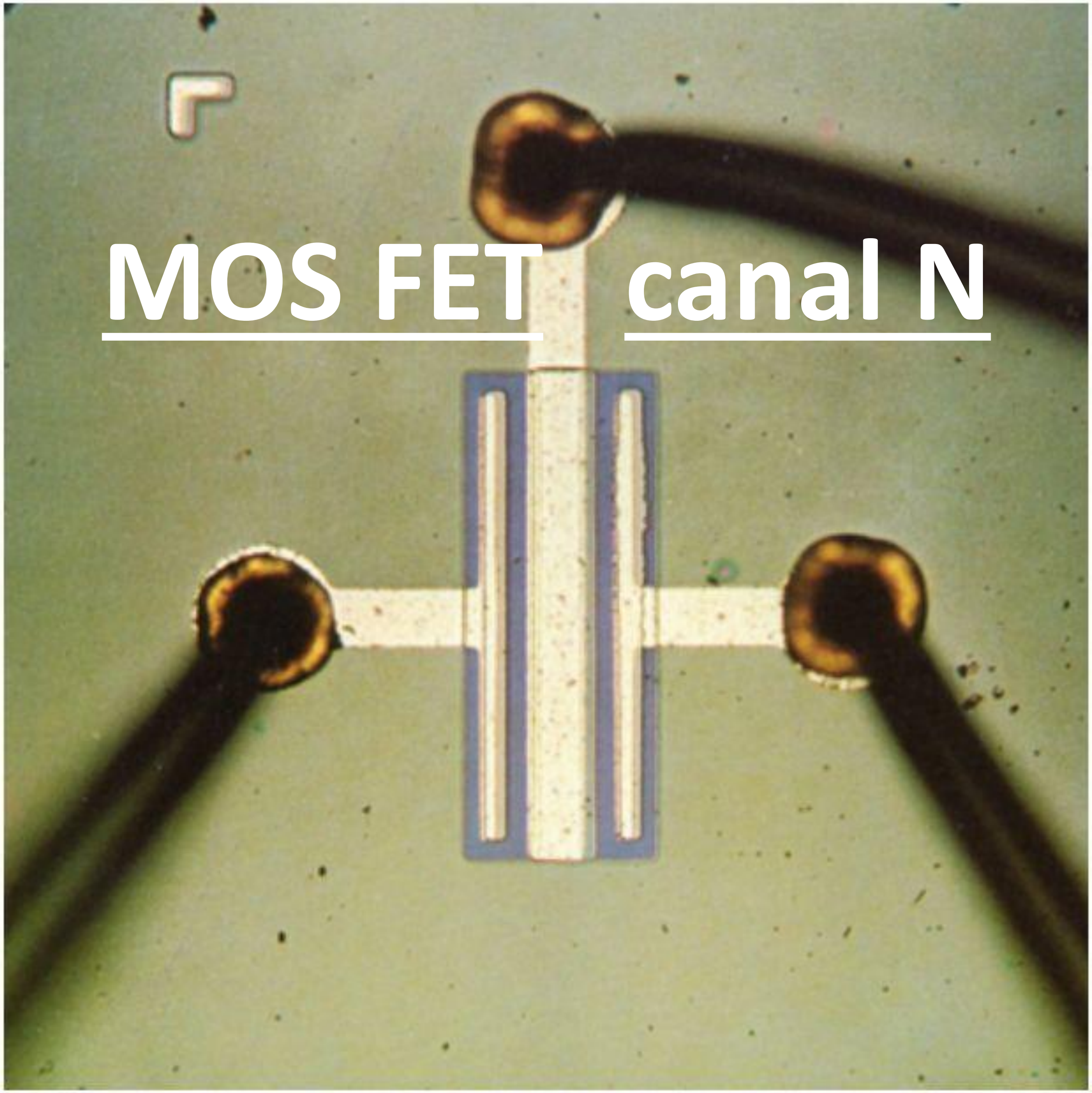


+
v_{GS}
−
G
$i_G = 0$
+
v_{DS} (pequeño)
−
i_D
D
S
$i_S = i_D$
i_D
n^+
n^+
canal n inducido
sustrato tipo p
B

Imagen de un MOS



MOS FET canal N



Fairchild FI 100 *p*-channel MOS switching transistor.

Credit: Fairchild Camera & Instrument Corporation.

Transistores

- BIPOLARES
  - NPN
  - PNP
- EFECTO DE CAMPO
  - UNIÓN
    - CANAL N (JFET-N)
    - CANAL P (JFET-P)
  - METAL-OXIDO-SEMICONDUCTOR
    - CANAL N (MOSFET-N)
      - ENRIQUECIMIENTO
      - DEPLEXION
    - CANAL P (MOSFET-P)
      - ENRIQUECIMIENTO
      - DEPLEXION

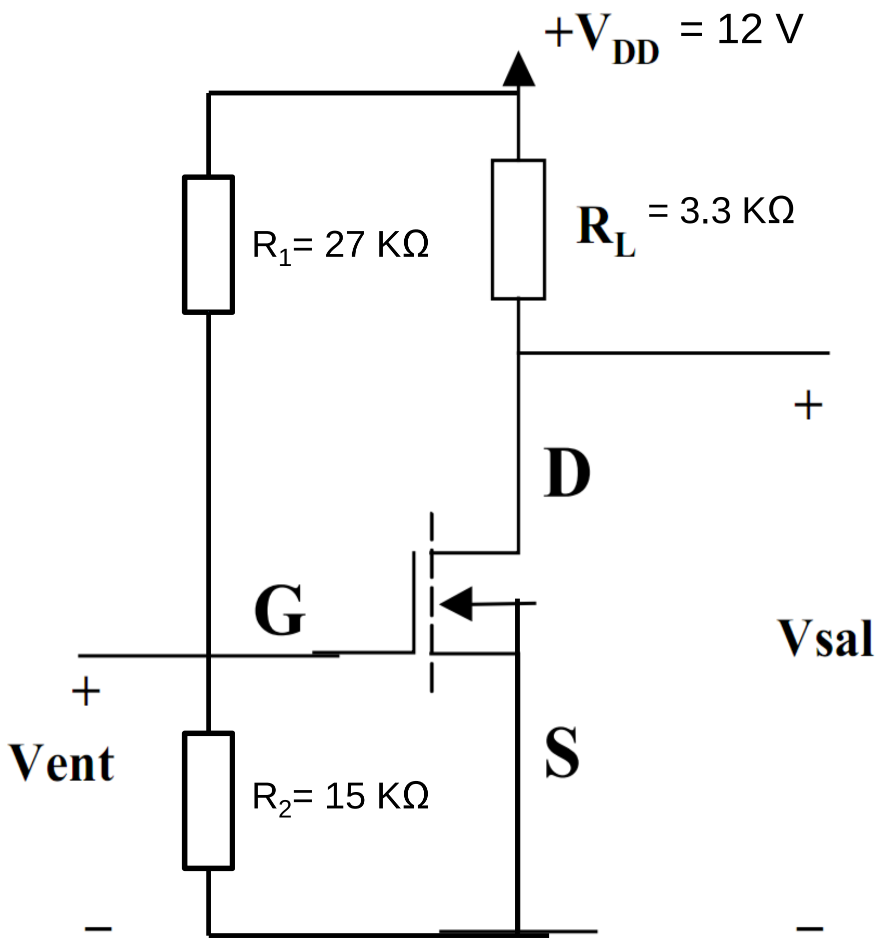
Dr Julius Lilienfield (Alemania) en 1926 patentó el concepto de "*Field Effect Transistor*".

Dr Martín Atalla y Dr Dawon Kahng desarrollaron el primer MOSFET en los laboratorios Bell en 1960

MOSFET

$\beta = 2\ mA/V^2$

$V_{TH} = 2\ V$



$$V_{GS} = \frac{V_{DD} \times R_2}{R_1 + R_2} \qquad V_{GS} = 4{,}28\ V$$

$$V_{Ds} = V_{DD} - I_{DS} \times R_L$$

Que ecuación uso para calcular I_{DS}

1 - Supongo Saturación

$V_{GS} > V_{TH}$ y $V_{GS} – V_{DS} < V_{TH}$

$$I_{DS} = \frac{\beta}{2}(V_{GS} - V_{TH})^2 \qquad I_{DS} = 5{,}2\ mA$$

$$V_{DS} = V_{DD} - I_{DS} \times R_L \qquad V_{DS} = -\ 5{,}2\ V$$

$$V_{GS} - V_{DS} = 9{,}48\ V$$

No verifica la desigualdad $V_{GS} – V_{DS} \nless V_{TH}$

2 - Supongo Óhmico

$V_{GS} > V_{TH}$ y $V_{GS} – V_{DS} > V_{TH}$

$I_{DS}=\beta*(V_{GS}-V_{TH})*V_{DS} – (\beta/2)*V_{DS}^2$

Supongo V_{DS} bajo

$I_{DS}\approx\beta*(V_{GS}-V_{TH})*V_{DS}$

Reemplazo $V_{DS} = V_{DD} – I_{DS} R_L$

$I_{DS}=\beta*(V_{GS}-V_{TH})* (V_{DD} –I_{DS} R_L)$

Resuelvo para I_{DS}

$$I_{DS} = \frac{\beta(V_{GS} - V_{TH})V_{DD}}{1 + \beta(V_{GS} - V_{TH})R_L}$$

$$V_{GS} = 4{,}28\,V$$

$I_{DS} = 3{,}4$ mA

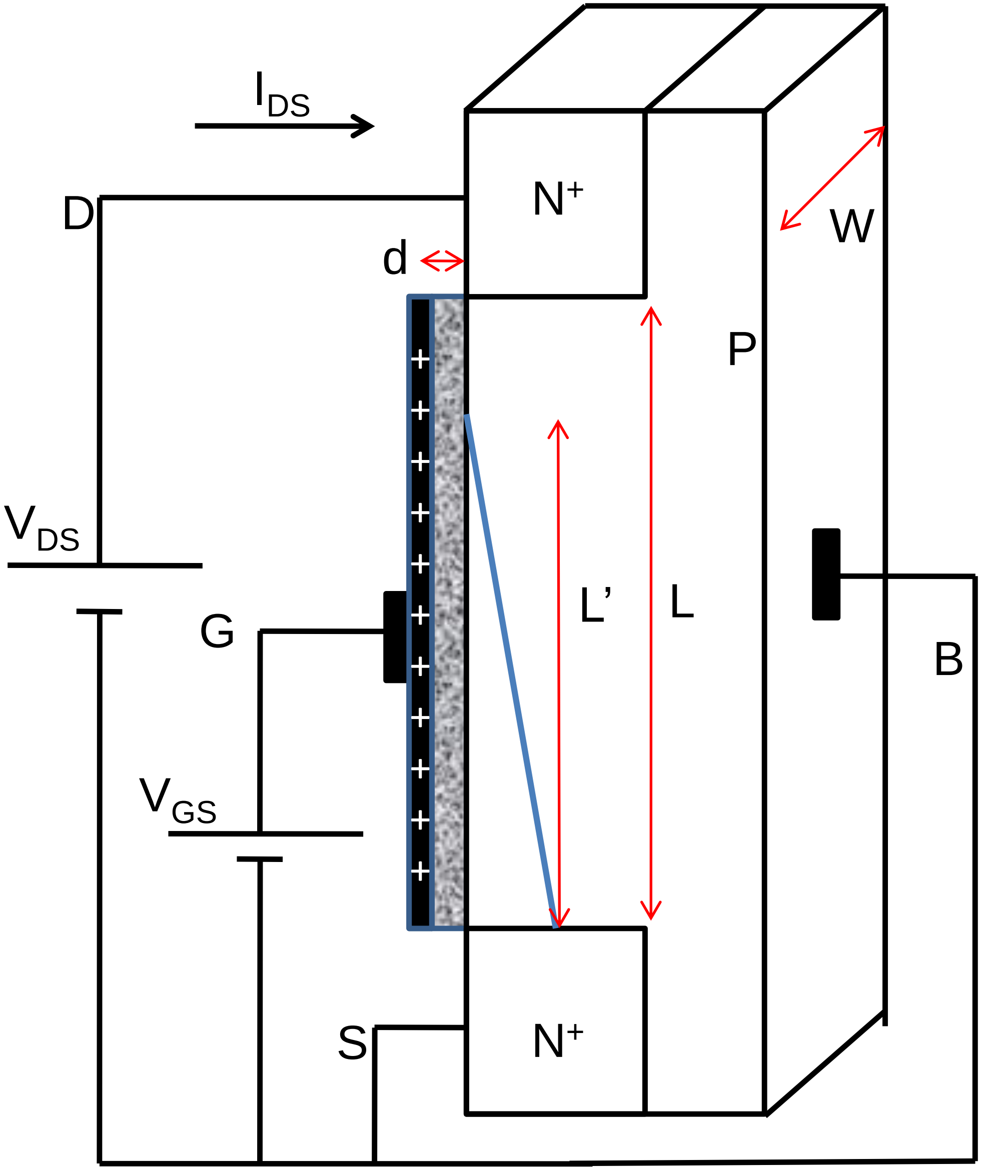
$V_{DS} = 0{,}78$ V

Verifico la desigualdad

$V_{GS} > V_{TH}$ y $V_{GS} – V_{DS} > V_{TH}$

Como paso a Saturación

Aumentando $V_{DS} \rightarrow$ Disminuyo R_L



$$I_{DS} = \frac{\beta}{2}(V_{GS} - V_{TH})^2$$

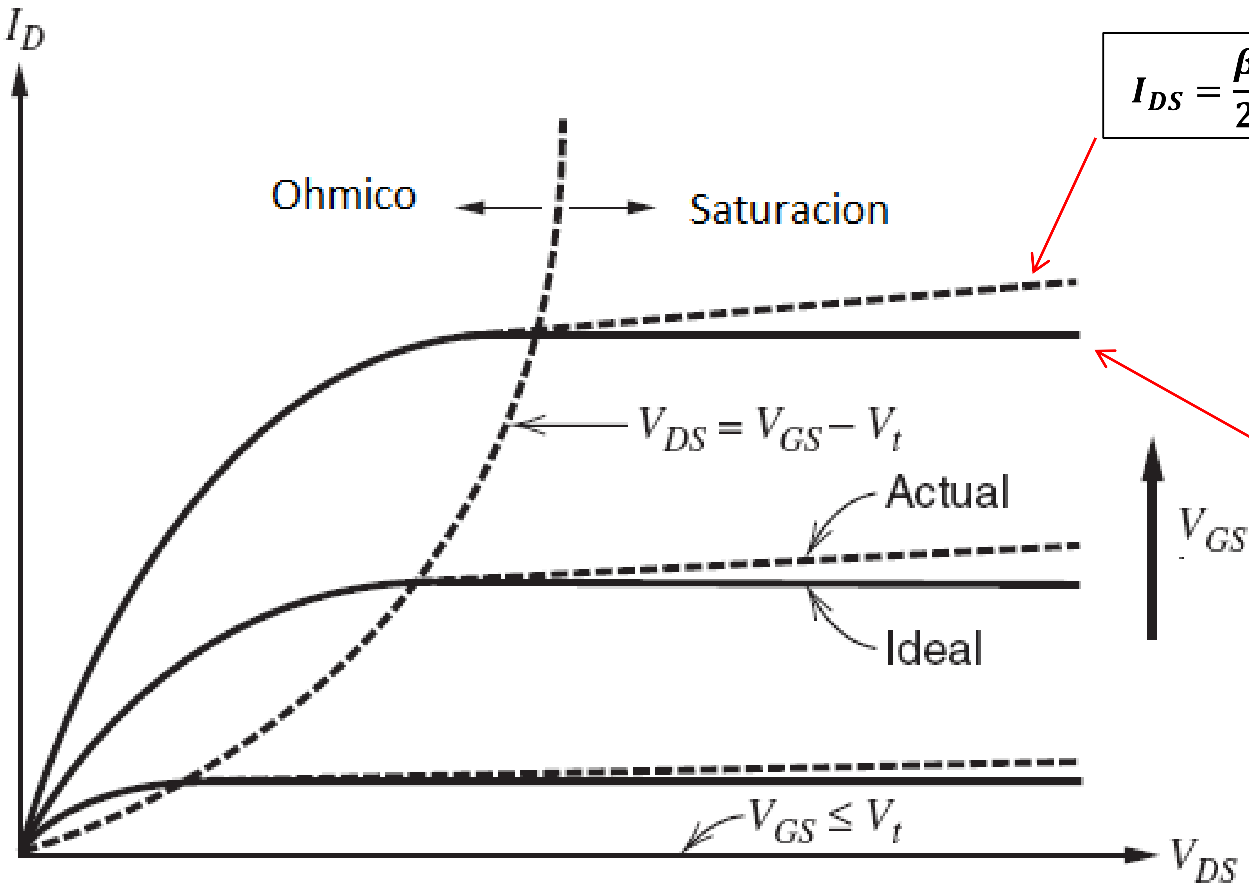
$$\beta = \frac{\mu\varepsilon}{d}\frac{W}{L} \qquad \beta' = \frac{\mu\varepsilon}{d}\frac{W}{L'}$$

$$\beta \rightarrow f(V_{DS})$$

$$I_{DS} \rightarrow f(V_{DS})$$

$$I_{DS} = \frac{\beta}{2}(1 + \lambda\, V_{DS})(V_{GS} - V_{TH})^2$$

Modulación del largo del canal

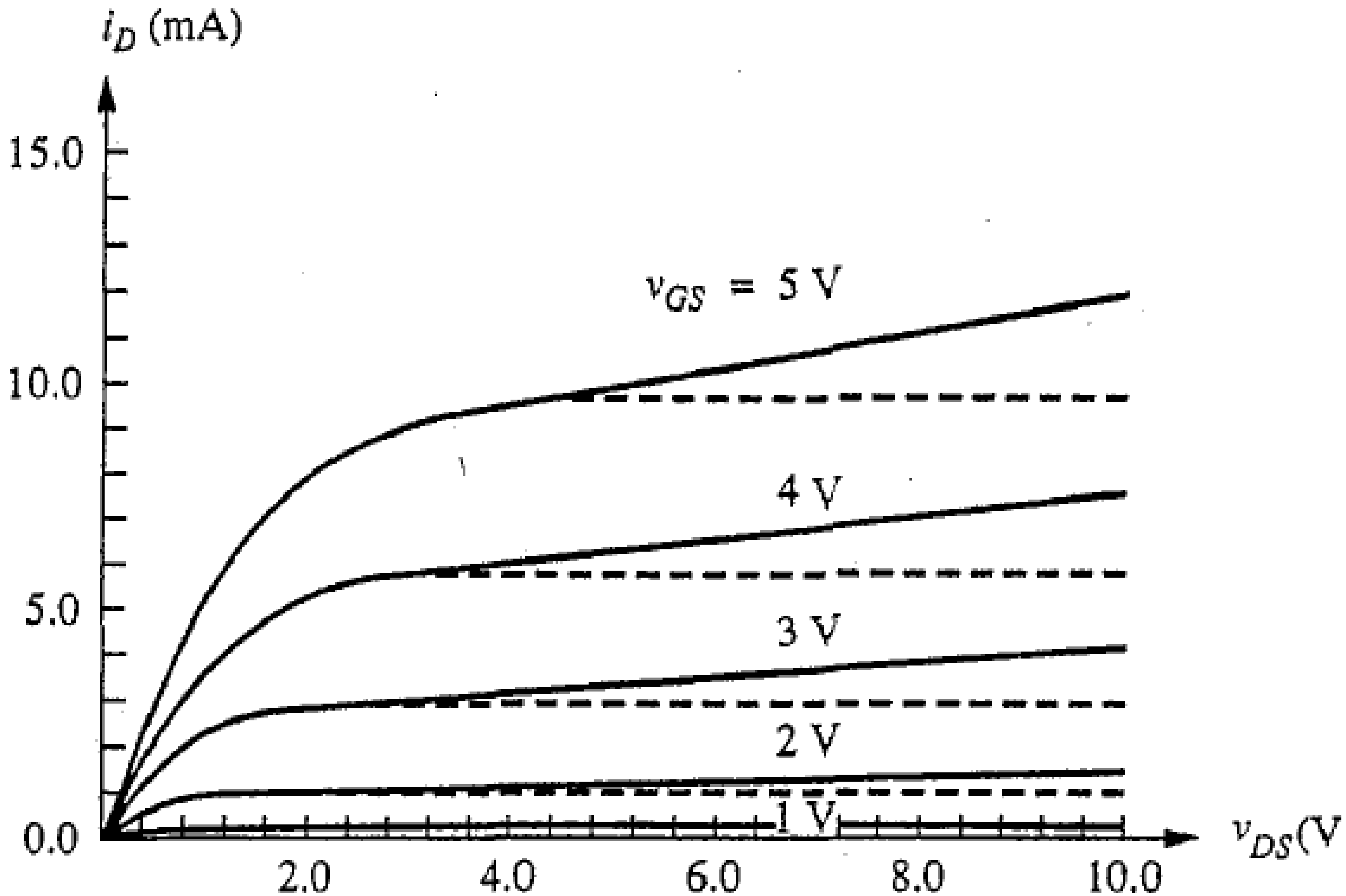


$$I_{DS} = \frac{\beta}{2}(1 + \lambda V_{DS})(V_{GS} - V_{TH})^2$$

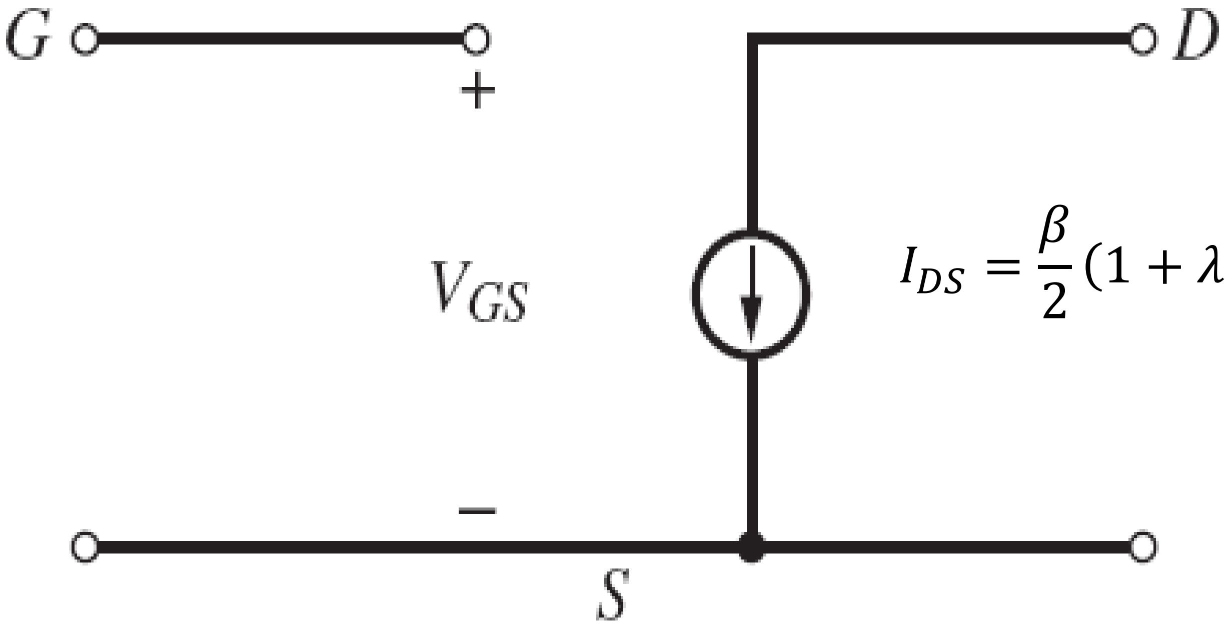
$$I_{DS} = \frac{\beta}{2}(V_{GS} - V_{TH})^2$$

Característica I_{DS} vs V_{DS} del MOSFET

Modulación del largo del canal

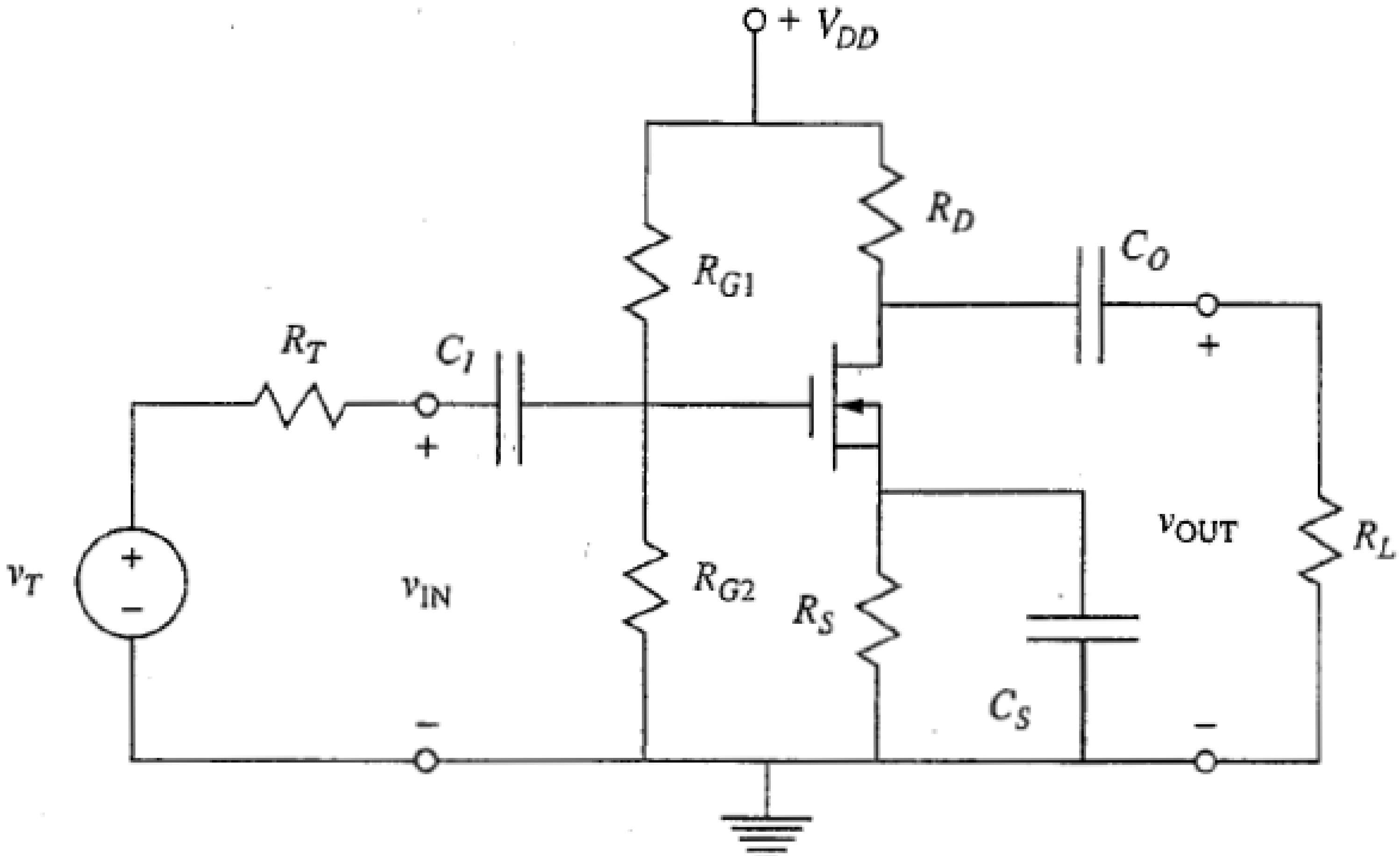


Modelo de Continua del MOSFET en zona de saturación



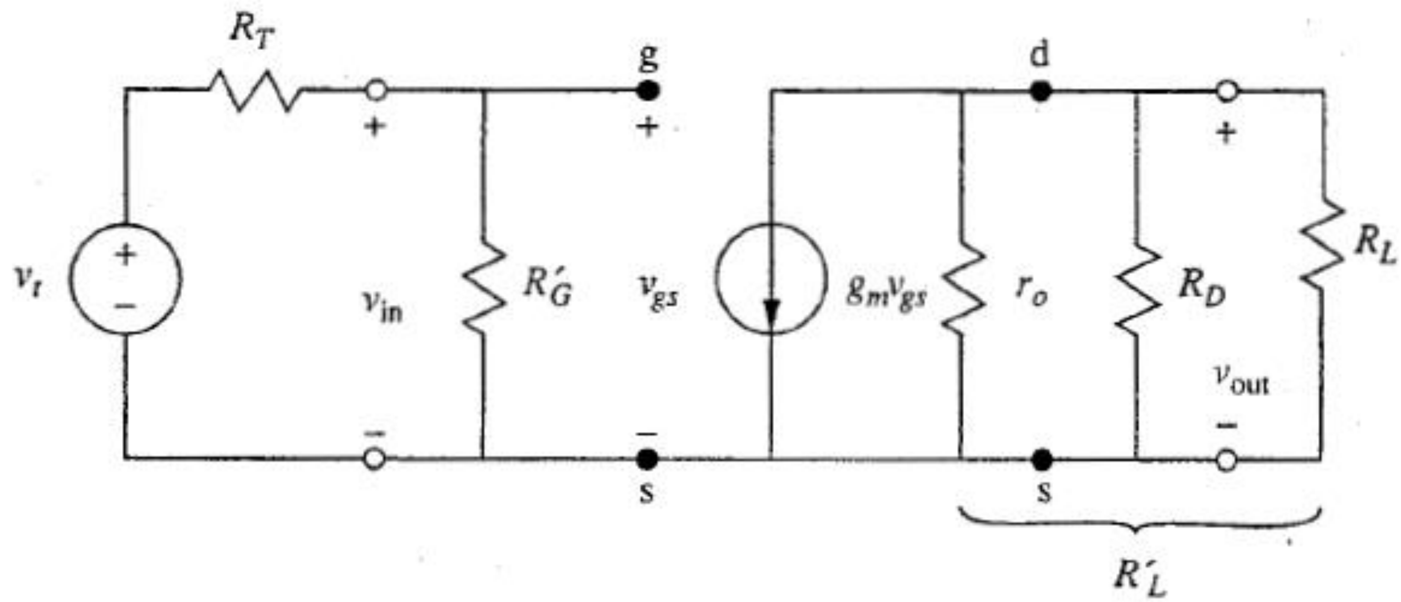
$$I_{DS} = \frac{\beta}{2}(1 + \lambda\, V_{DS})(V_{GS} - V_{TH})^2$$

Amplificador con MOSFET



Amplificador de Fuente Común

Modelo de Pequeña Señal del Amplificador de Fuente Común



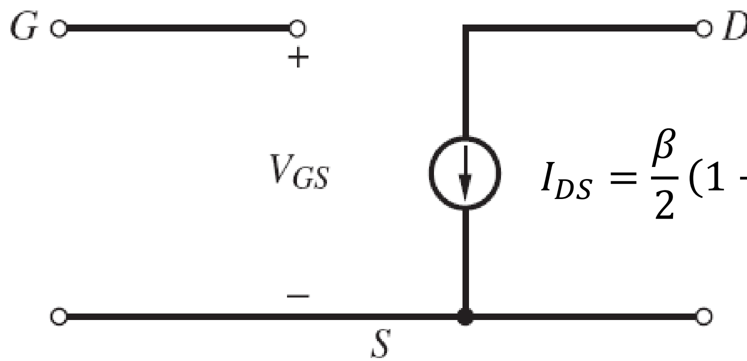
$$v_{out} = -g_m v_{gs} R'_L$$

$$A_V = \frac{v_{out}}{v_{in}}$$

$$v_{in} = v_{gs}$$

$$A_v = -g_m R'_L$$

Si el MOSFET esta polarizado en SATURACION



$$I_{DS} = \frac{\beta}{2}(1 + \lambda\, V_{DS})(V_{GS} - V_{TH})^2$$

$$g_m = \left.\frac{dI_{DS}}{dV_{GS}}\right|_{\overline{Q}} \qquad r_0 = \left.\frac{dV_{DS}}{dI_{DS}}\right|_{\overline{Q}}$$

$$g_m = \beta(1 + \lambda\, V_{DS})(V_{GSP} - V_{TH})\Big|_{\overline{Q}} \qquad r_0 = \left.\frac{1}{\lambda\, I_{DSP}}\right|_{\overline{Q}}$$

En el punto de polarización (Q)

$V_{GS} = V_{GSP}$ - $I_{DS} = I_{DSP}$ - $V_{DS} = V_{DSP}$

Ganancia de tensión $\Rightarrow$ $A_V = -\beta(1+\lambda\, V_{DS})(V_{GSP} - V_{TH})R'_L$

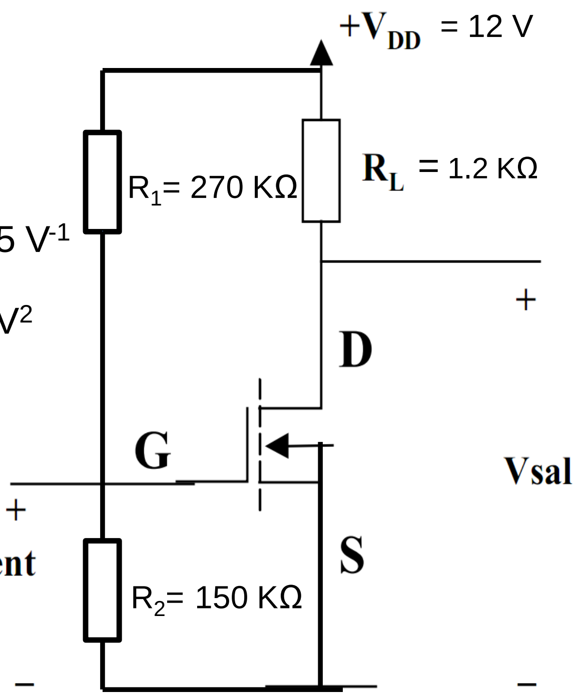
Resistencia de entrada $\Rightarrow$ $R_i = R'_G$

Resistencia de salida $\Rightarrow$ $R_o = R'_L$

λ = 0.0125 V^{-1}

β = 2 mA/V^2

V_{TH} = 2 V



$$V_{GSP} = V_{DD}\frac{R_2}{R_1 + R_2} = 4{,}28\ V$$

$$I_{DSP} = \frac{\beta}{2}(V_{GSP} - V_{TH})^2 = 5{,}2\ mA$$

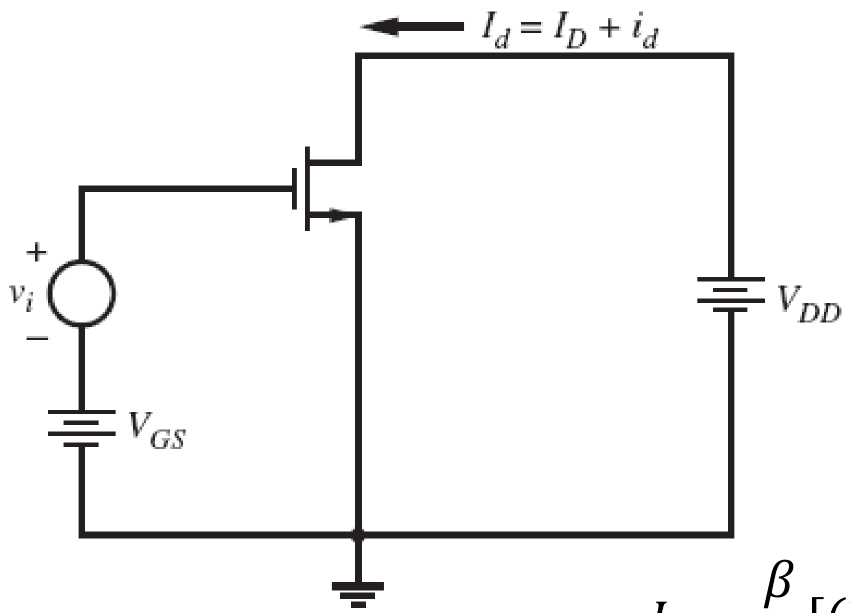
$$V_{DSP} = V_{DD} - I_{DSP}R_L = 5{,}76\ V$$

$$V_{GSP} - V_{DSP} = -1{,}48 < V_{TH}$$ $\Rightarrow$ SATURACION

$$A_V = -\beta(1+\lambda\, V_{DS})(V_{GSP} - V_{TH})R'_L = -5{,}48$$

$$R_i = R'_G = 96\ K\Omega$$

Validez del Modelo de Pequeña Señal del MOSFET



Considerando $\lambda V_{DS} \ll 1$

$$I_d = \frac{\beta}{2}(V_{GS} + v_i - V_{TH})^2$$

$$I_d = \frac{\beta}{2}[(V_{GS} - V_{TH})^2 + 2(V_{GS} - V_{TH})v_i + {v_i}^2]$$

$$I_d = I_D + \frac{\beta}{2}[2(V_{GS} - V_{TH})v_i + {v_i}^2]$$

$$i_d = I_d - I_D$$

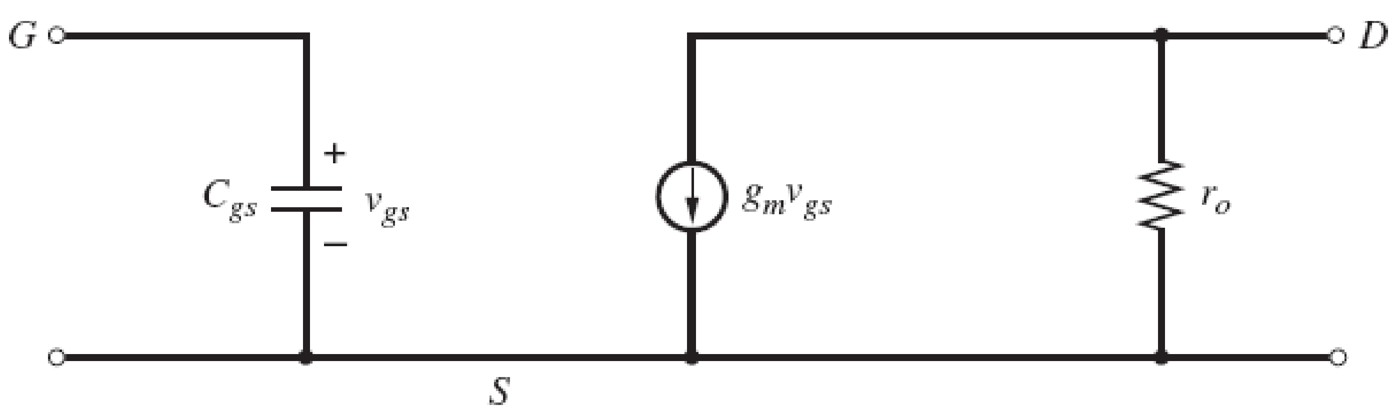
$$i_d = \frac{\beta}{2}[2(V_{GS} - V_{TH})v_i + {v_i}^2]$$

$$i_d = \beta(V_{GS} - V_{TH})\ v_i \left[1 + \frac{v_i}{2(V_{GS} - V_{TH})}\right]$$

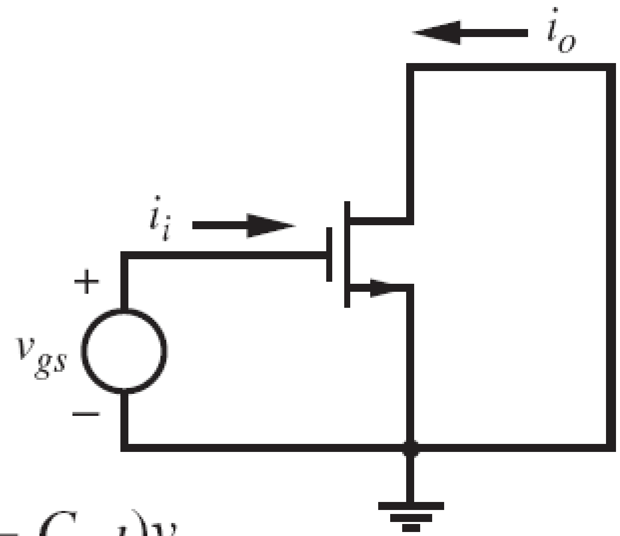
Si $v_i \ll 2(V_{GS} - V_{TH})$ $\Rightarrow$ Condición para la validez del modelo de pequeña señal

$$i_d = \beta(V_{GS} - V_{TH})\, v_i$$

$$g_m = \beta(V_{GS} - V_{TH})$$

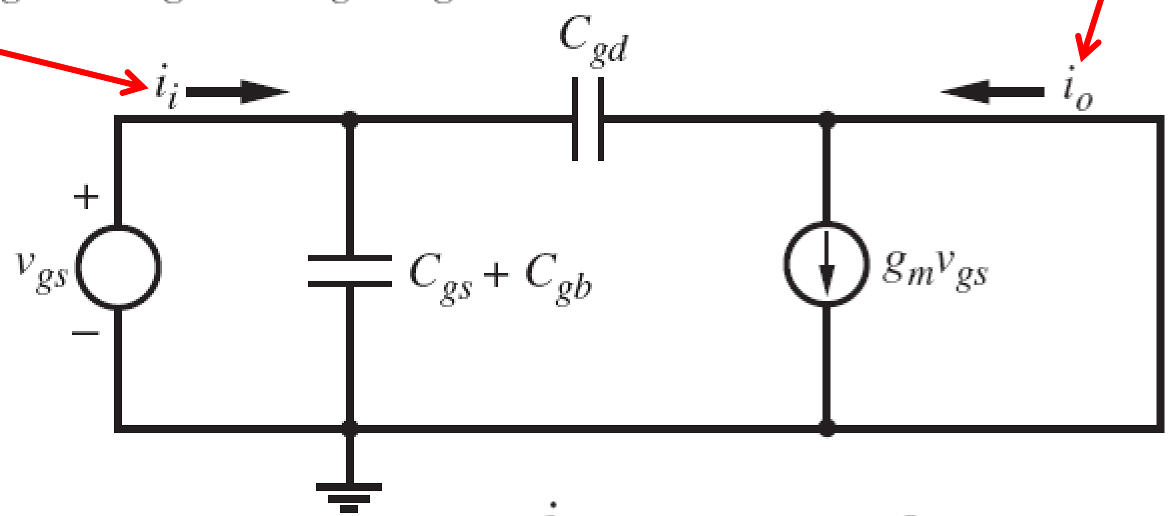


Respuesta en frecuencia del MOSFET



$$i_i = s(C_{gs} + C_{gb} + C_{gd})v_{gs}$$

$$i_o \simeq g_m v_{gs}$$



$$\frac{i_o}{i_i} \simeq \frac{g_m}{s(C_{gs} + C_{gb} + C_{gd})}$$

$$\frac{i_o}{i_i} \simeq \frac{g_m}{j\omega(C_{gs} + C_{gb} + C_{gd})}$$

$$\omega = \omega_T = \frac{g_m}{C_{gs} + C_{gb} + C_{gd}}$$

$$f_T = \frac{1}{2\pi}\omega_T = \frac{1}{2\pi}\frac{g_m}{C_{gs} + C_{gb} + C_{gd}}$$

$$C_{gs} \gg (C_{gb} + C_{gd}) \Rightarrow f_T = \frac{1}{2\pi}\frac{g_m}{C_{gs}}$$

$$f_T = \frac{1}{2\pi}\frac{\beta(V_{GS} - V_{TH})}{C_{gs}}$$

$$\beta = \frac{\mu\varepsilon}{d}\frac{W}{L}$$

$$f_T = \frac{1}{2\pi}\frac{\mu}{L^2}(V_{GS} - V_{TH})$$

$$C_{gs} = \varepsilon\frac{W\ L}{d}$$

$$\frac{1}{T_T} = \frac{\mu\, V_{DS}}{L^2}$$

$$f_T = \frac{1}{2\pi}\frac{1}{T_T}$$