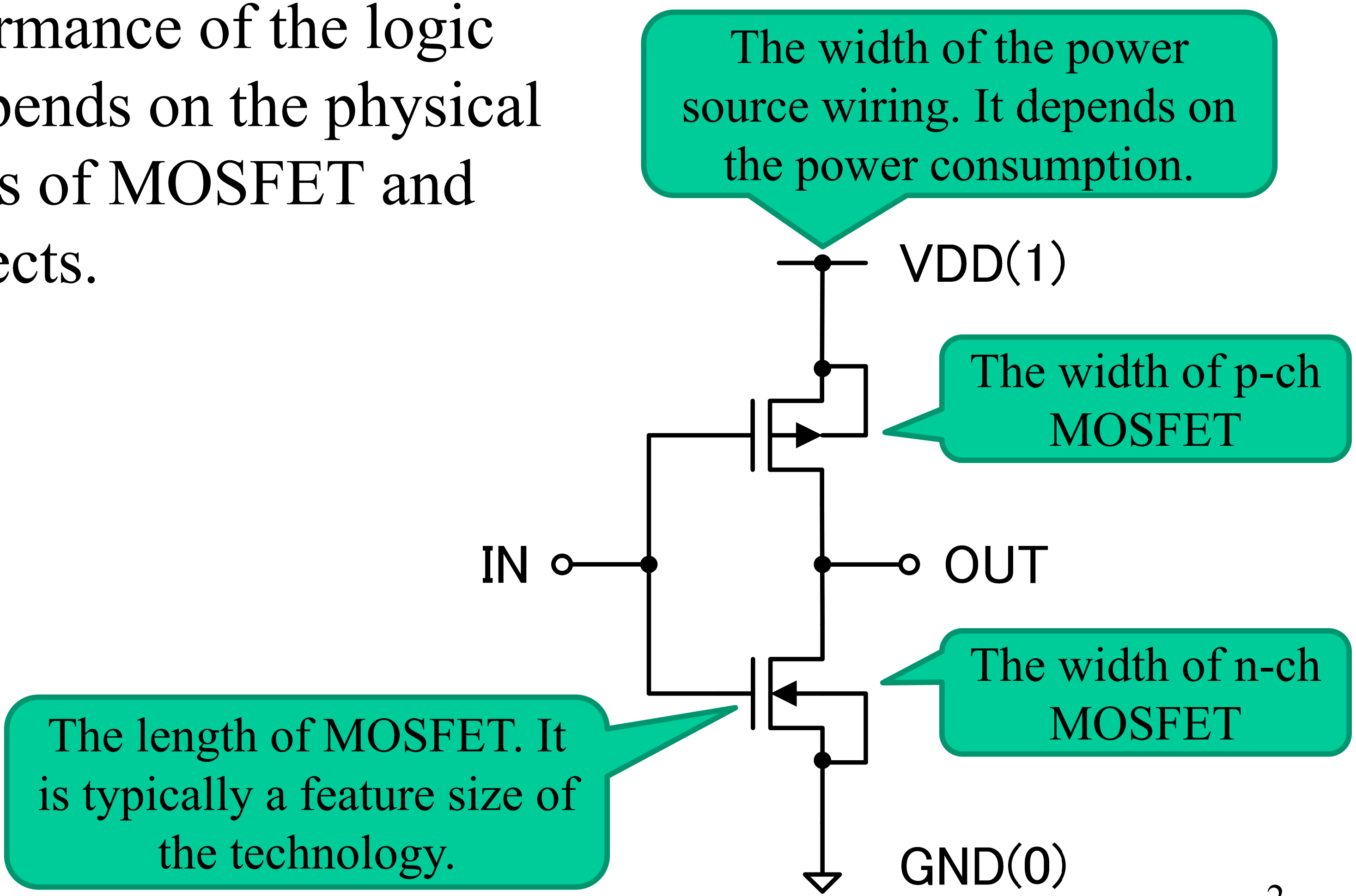
4.1 I-V characteristics of MOSFET

Current in MOSFET

Physical design

The performance of the logic circuit depends on the physical parameters of MOSFET and interconnects.

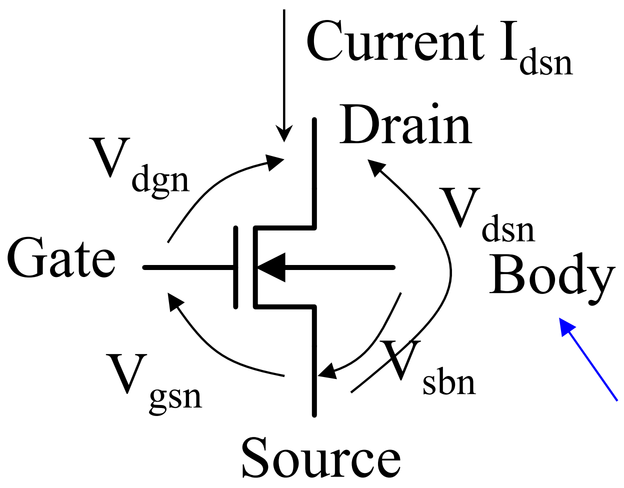
Physical parameters



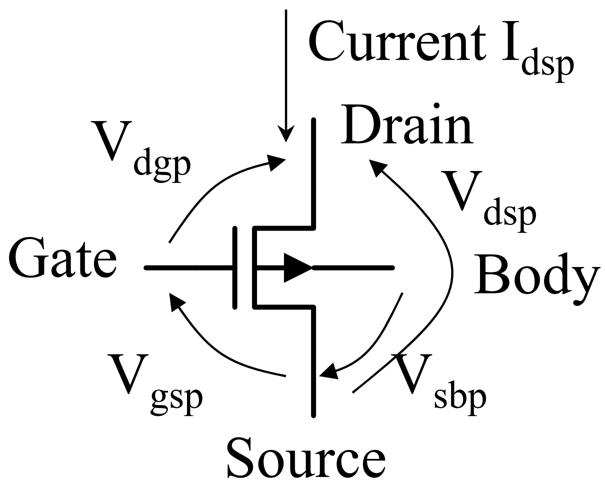
4.1.1 Summary of I-V characteristics

Definition of voltage and current in MOSFET

n-ch MOSFET



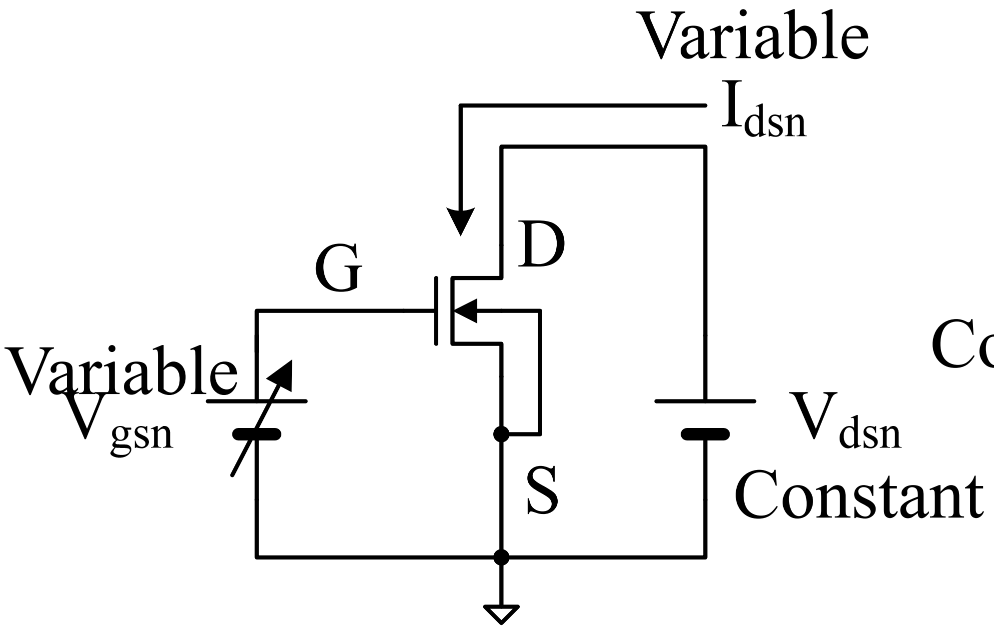
p-ch MOSFET



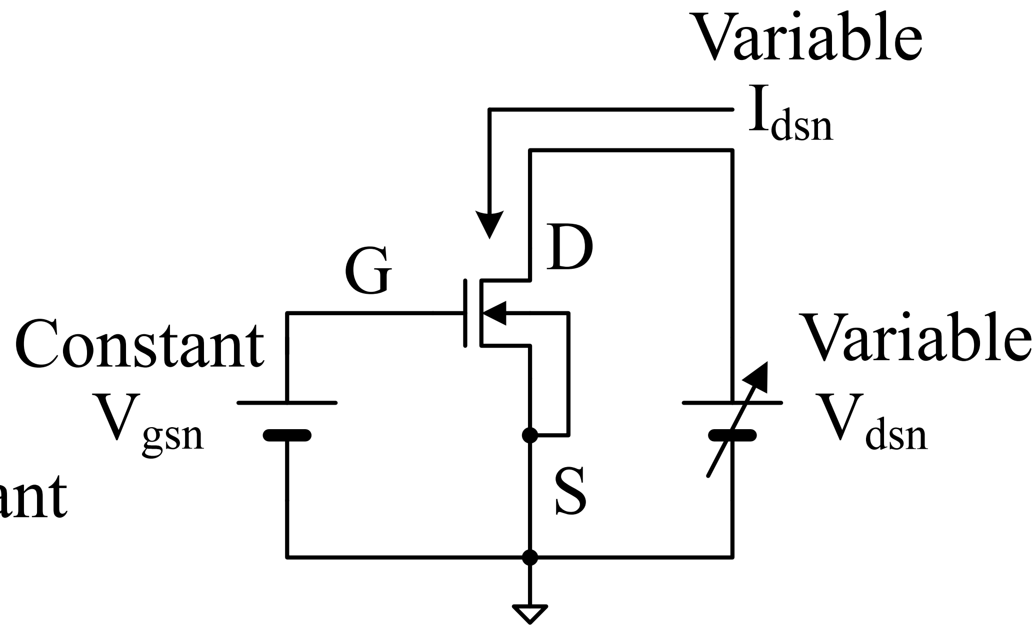
Note: A p-ch MOSFET operates with negative voltages and current.

Measurement circuits of I-V characteristics

When $V_{sbn} = 0$, the variables are V_{gsn}, V_{dsn}, and I_{dsn}.



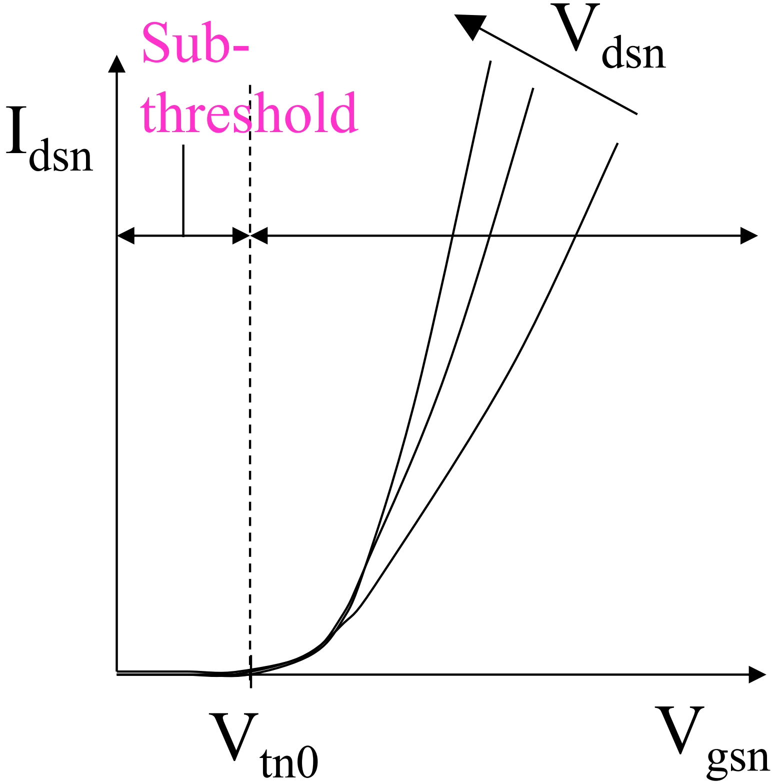
I_{dsn}-V_{gsn} characteristic



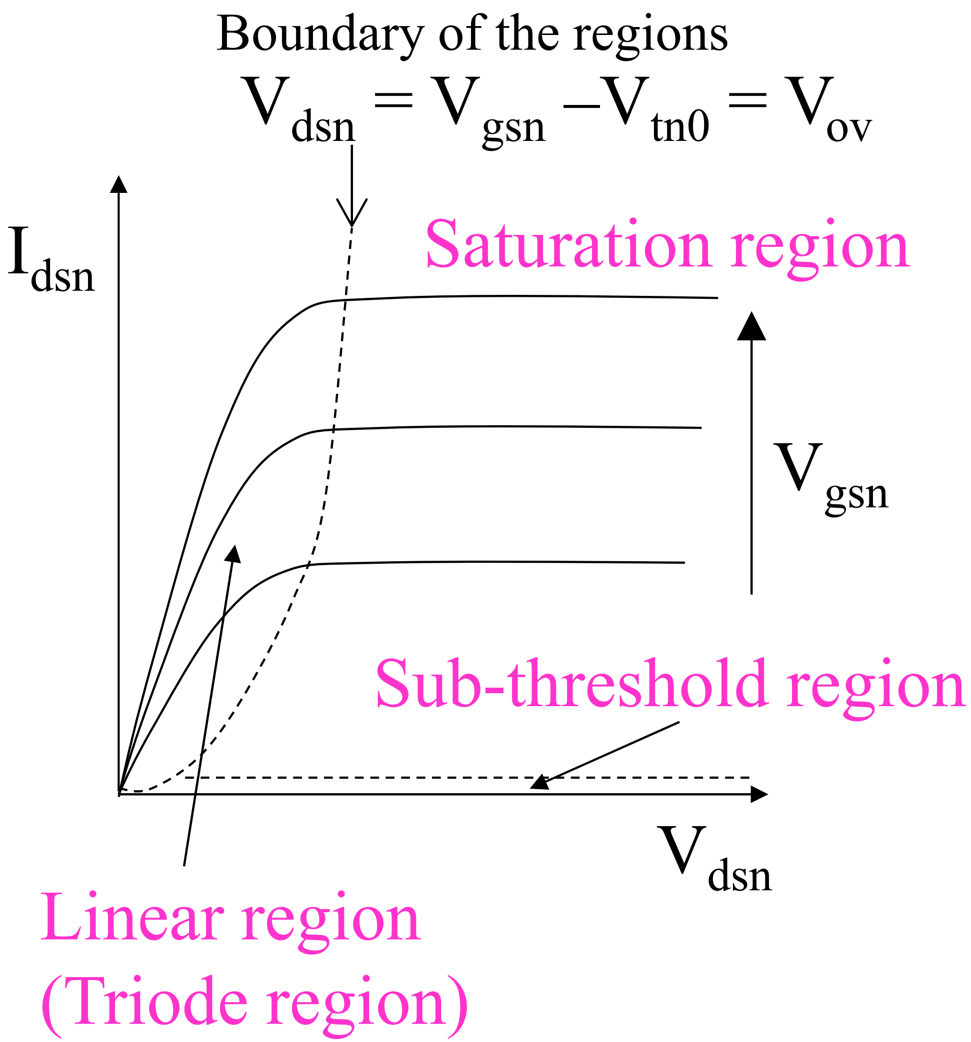
I_{dsn}-V_{dsn} characteristic

Nore: The values of V_{gsn}, V_{dsn}, I_{dsn} are negative for p-ch MOSFET.

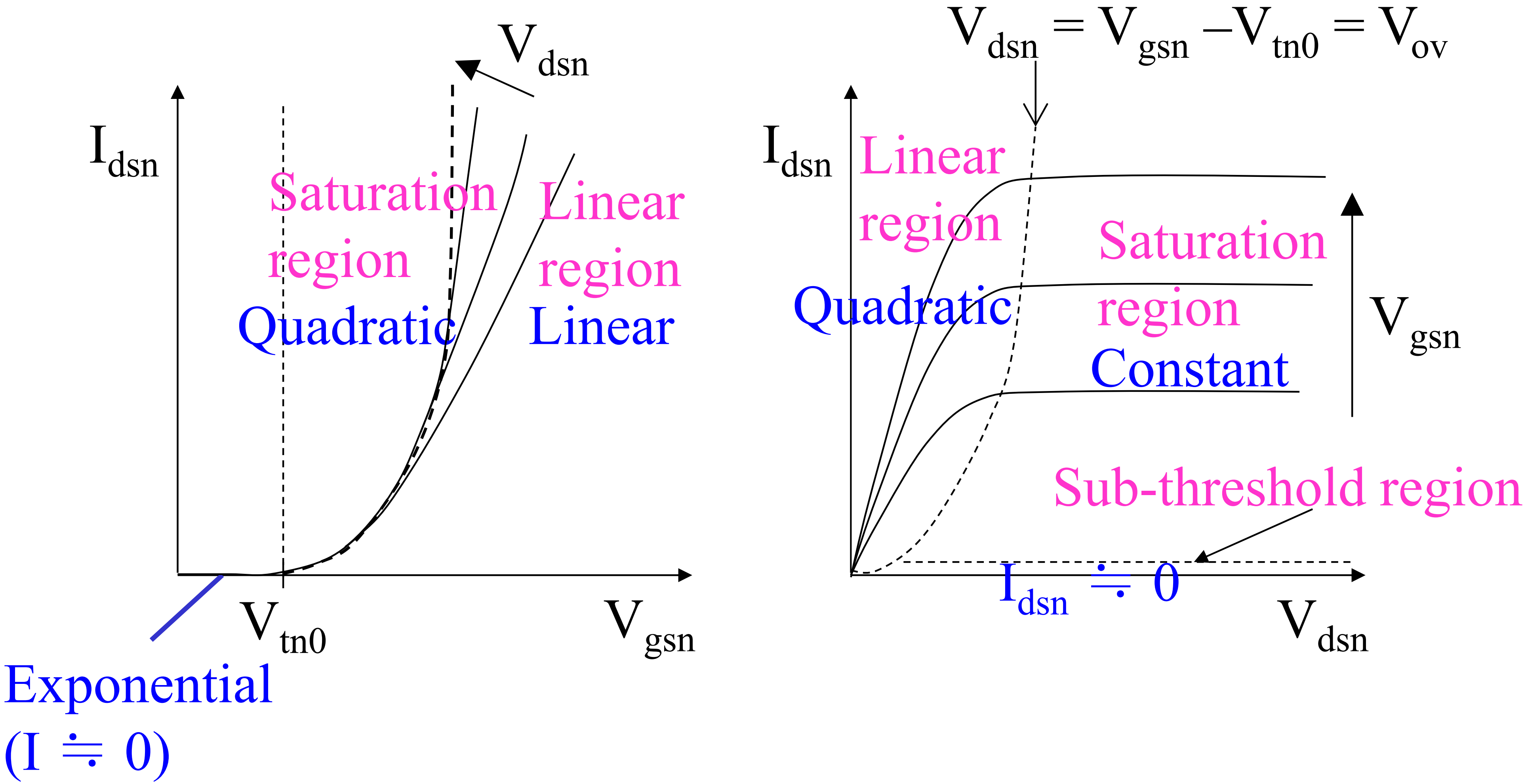
Regions of I-V characteristics



Threshold voltage
(閾値電圧)
is controlled by the manufacture.

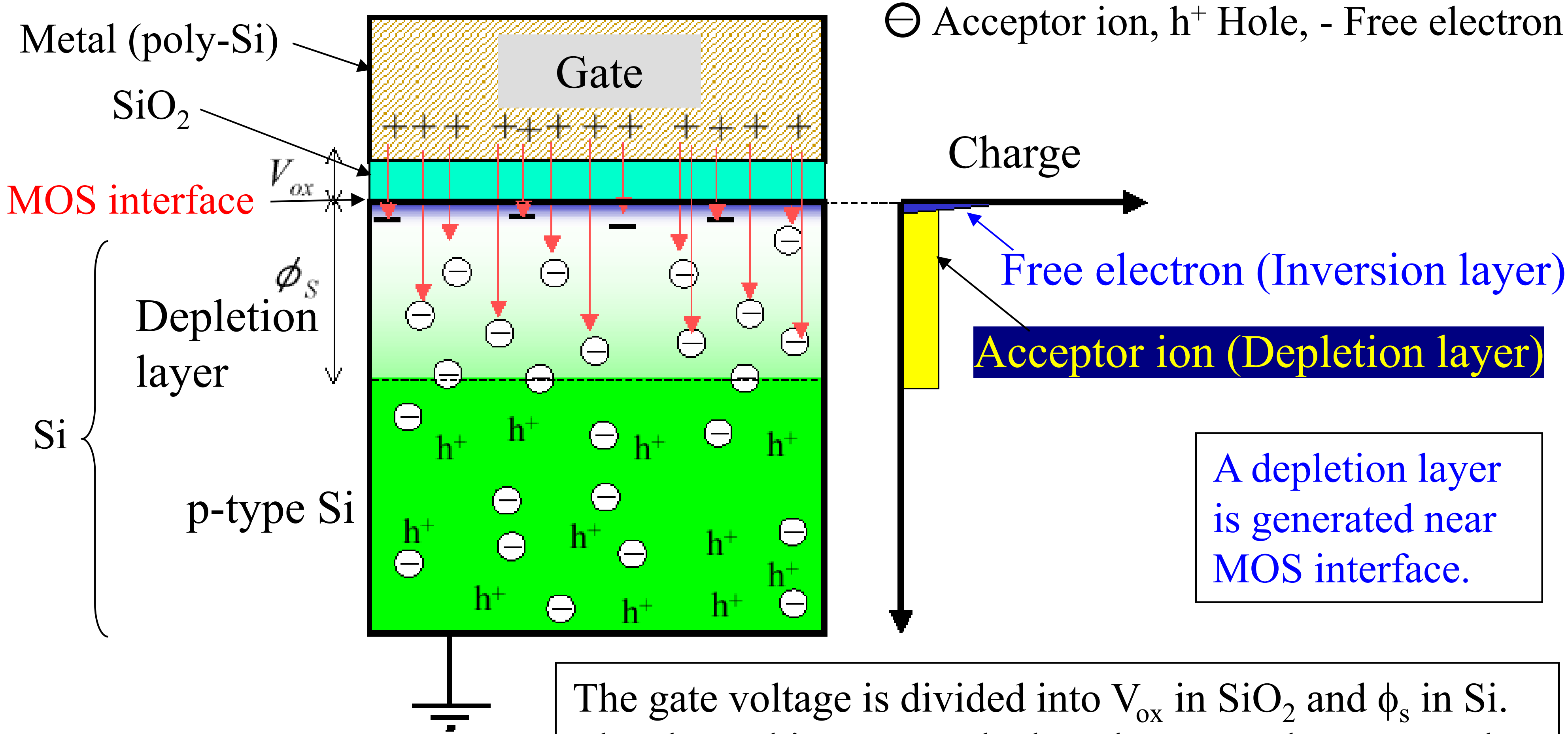


Approximate expression of I-V characteristics



Threshold voltage

(Animation)



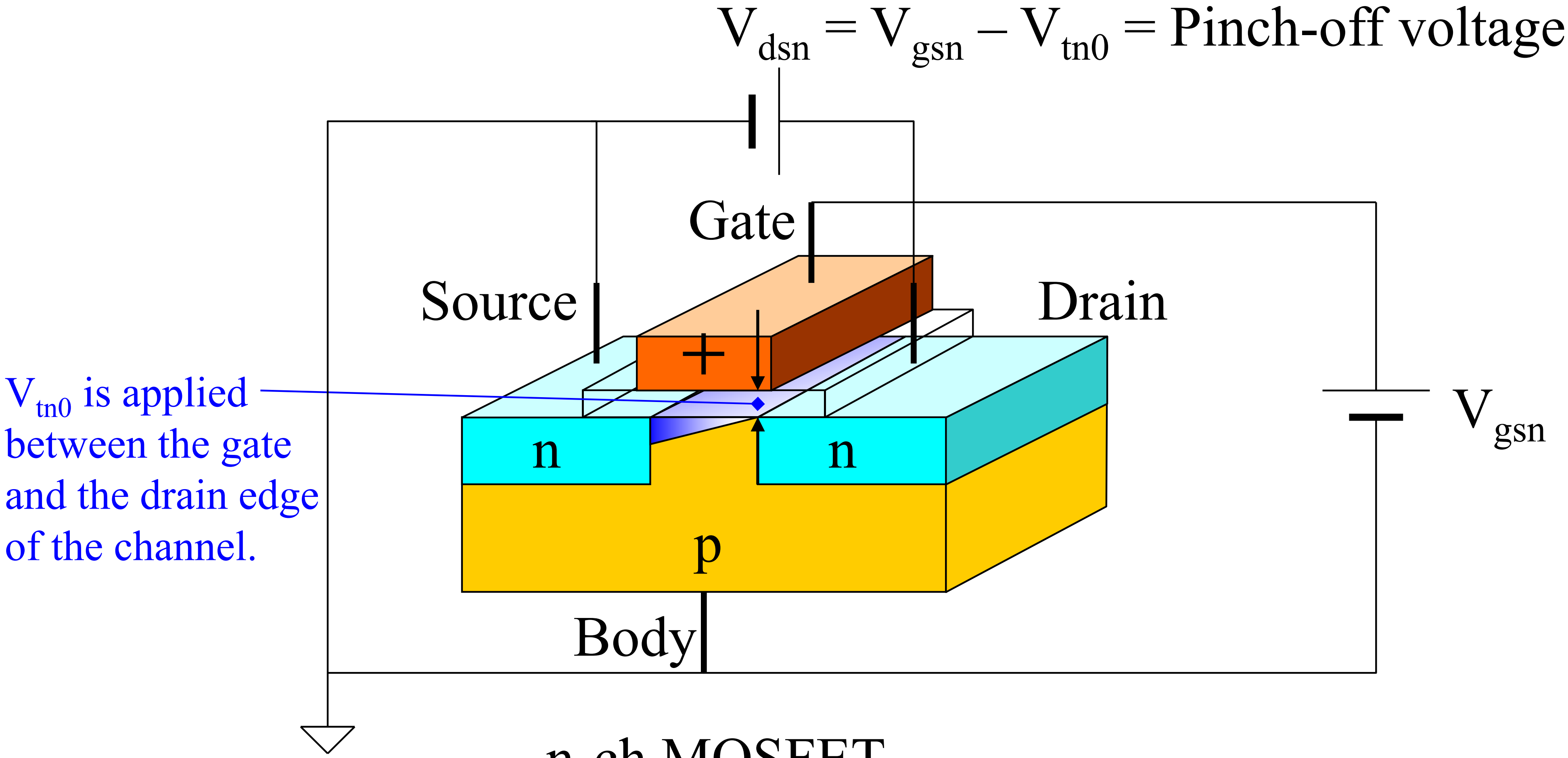
A depletion layer is generated near MOS interface.

The gate voltage is divided into V_{ox} in SiO_2 and ϕ_s in Si. The channel is generated when the gate voltage exceeds the threshold voltage.

4.1.2 Saturation characteristic

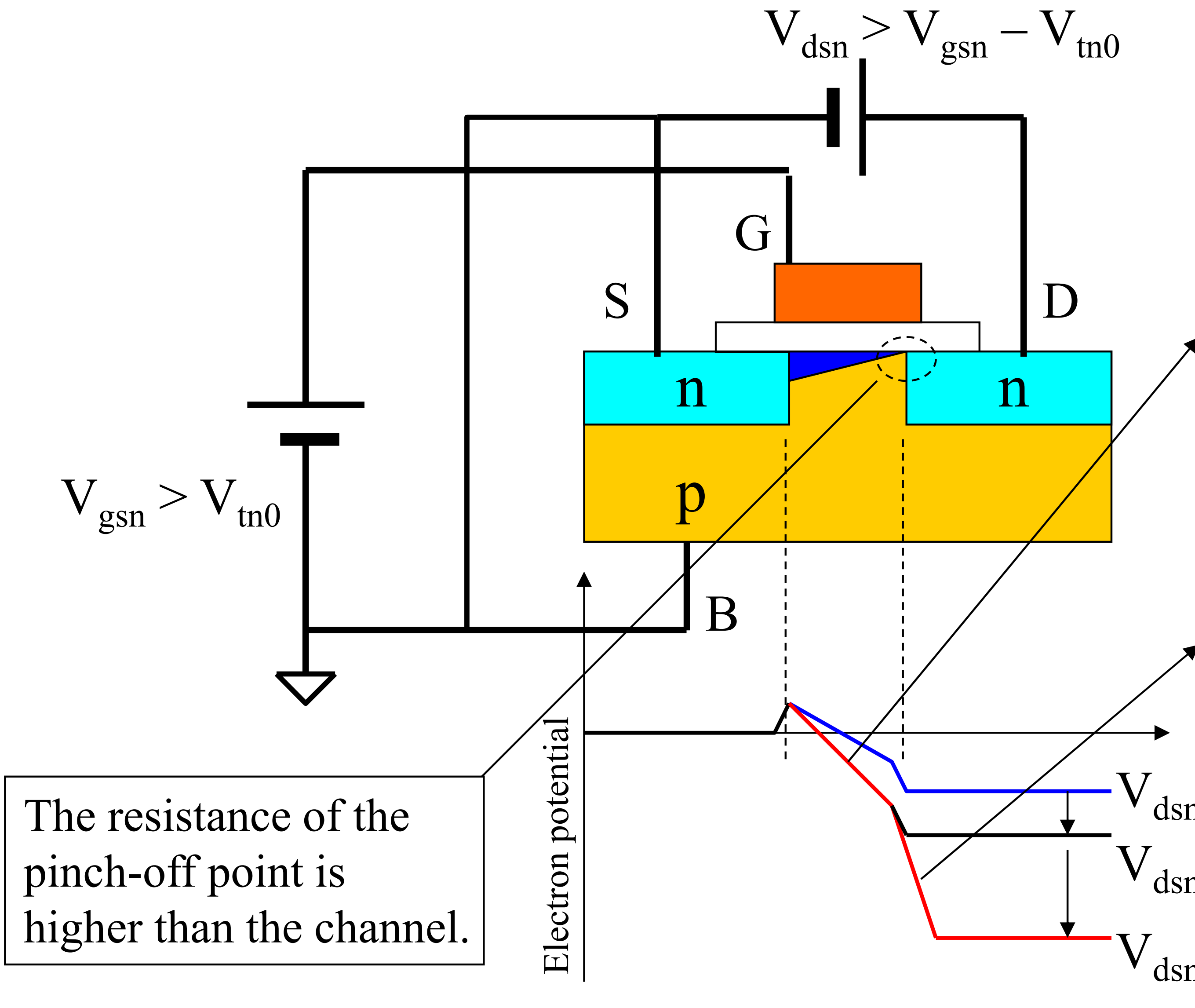
Pinch-off

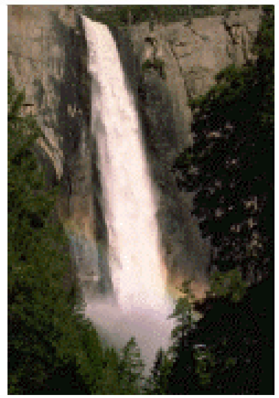
When $V_{dsn} = V_{gsn} - V_{tn0}$, the channel disappears at the drain edge.



n-ch MOSFET

Saturation of the current

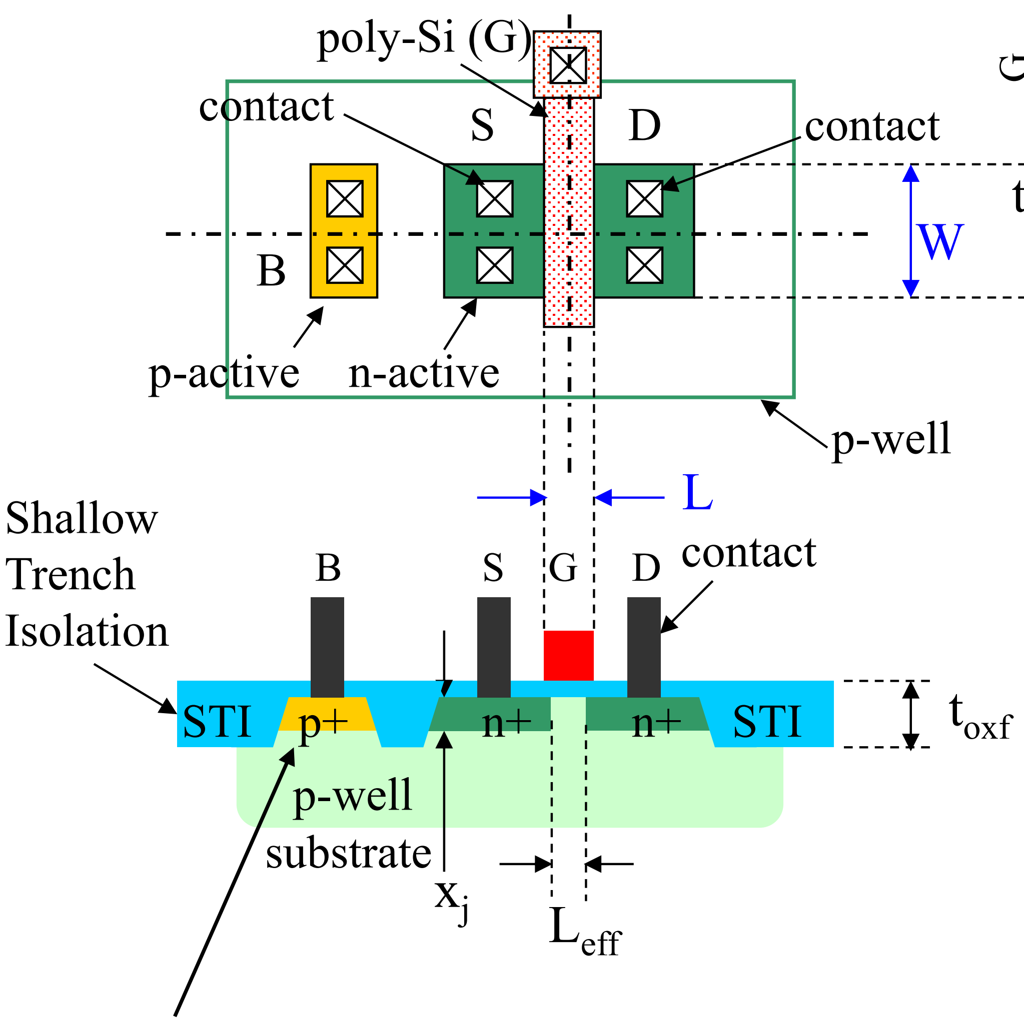


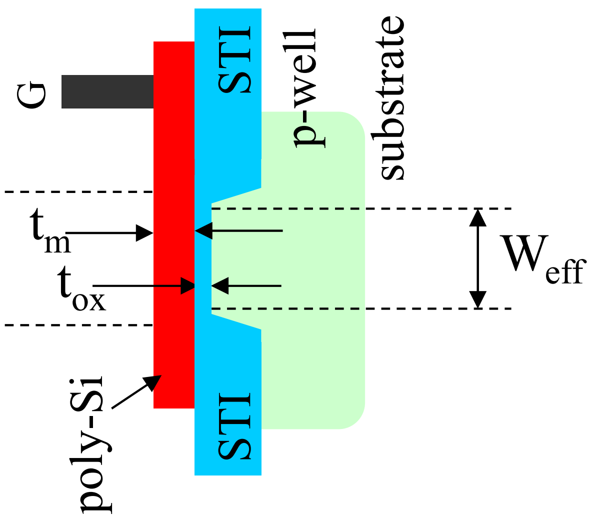


The flow rate of the water does not depend on the waterfall.

4.1.3 Mathematical expression of I-V characteristics

Shape and size of MOSFET





L: Gate length （ゲート長）
W: Gate width （ゲート幅）
L_{eff}: Effective channel length
W_{eff}: Effective channel width
x_j: Junction depth
t_{ox}: Gate oxide thickness（ゲート酸化膜厚）
t_{oxf}: Field oxide thickness
t_m: Poly-Si thickness

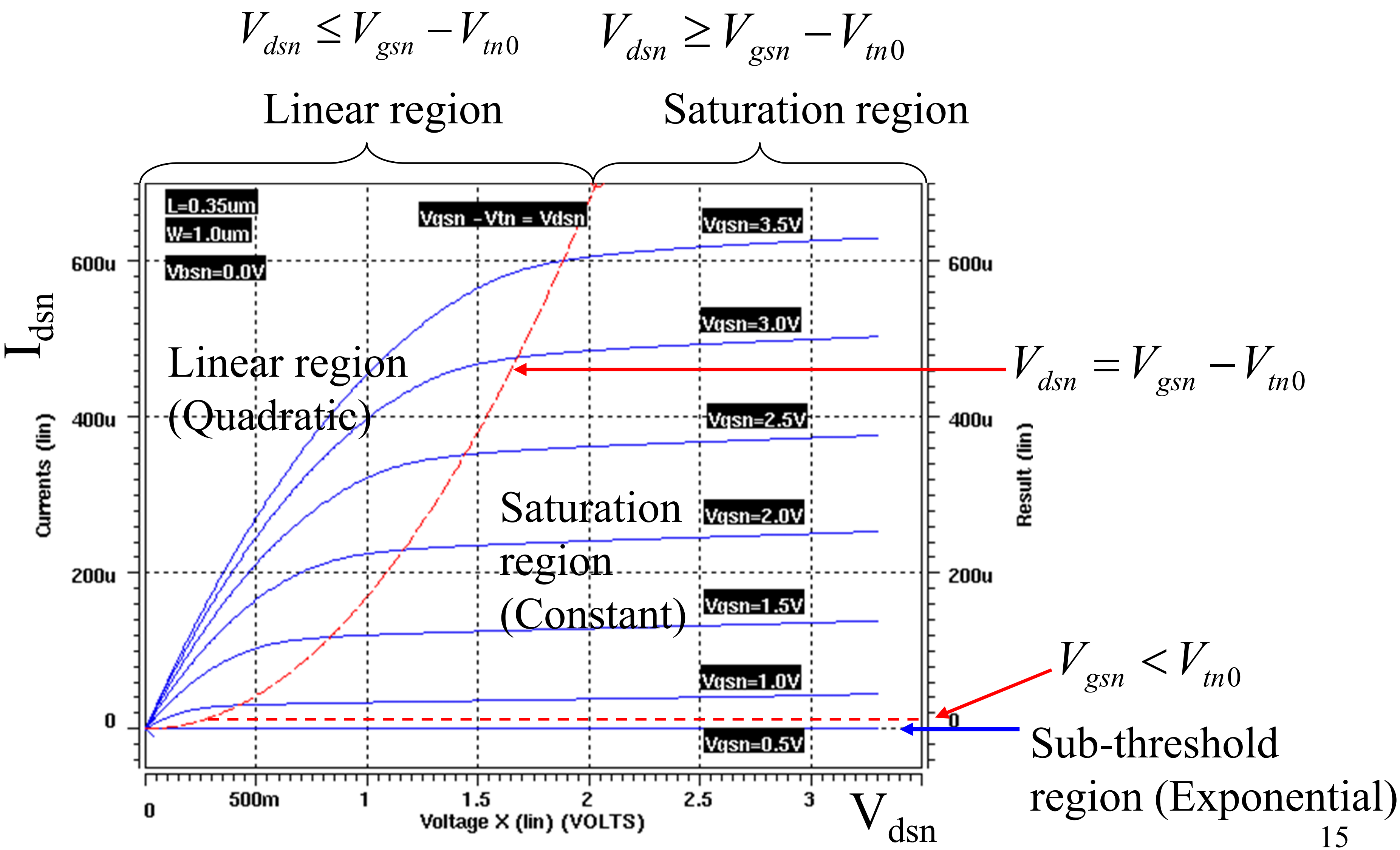
Note: p+ and n+ mean the highly-doped semiconductors.

Parameters of MOSFET

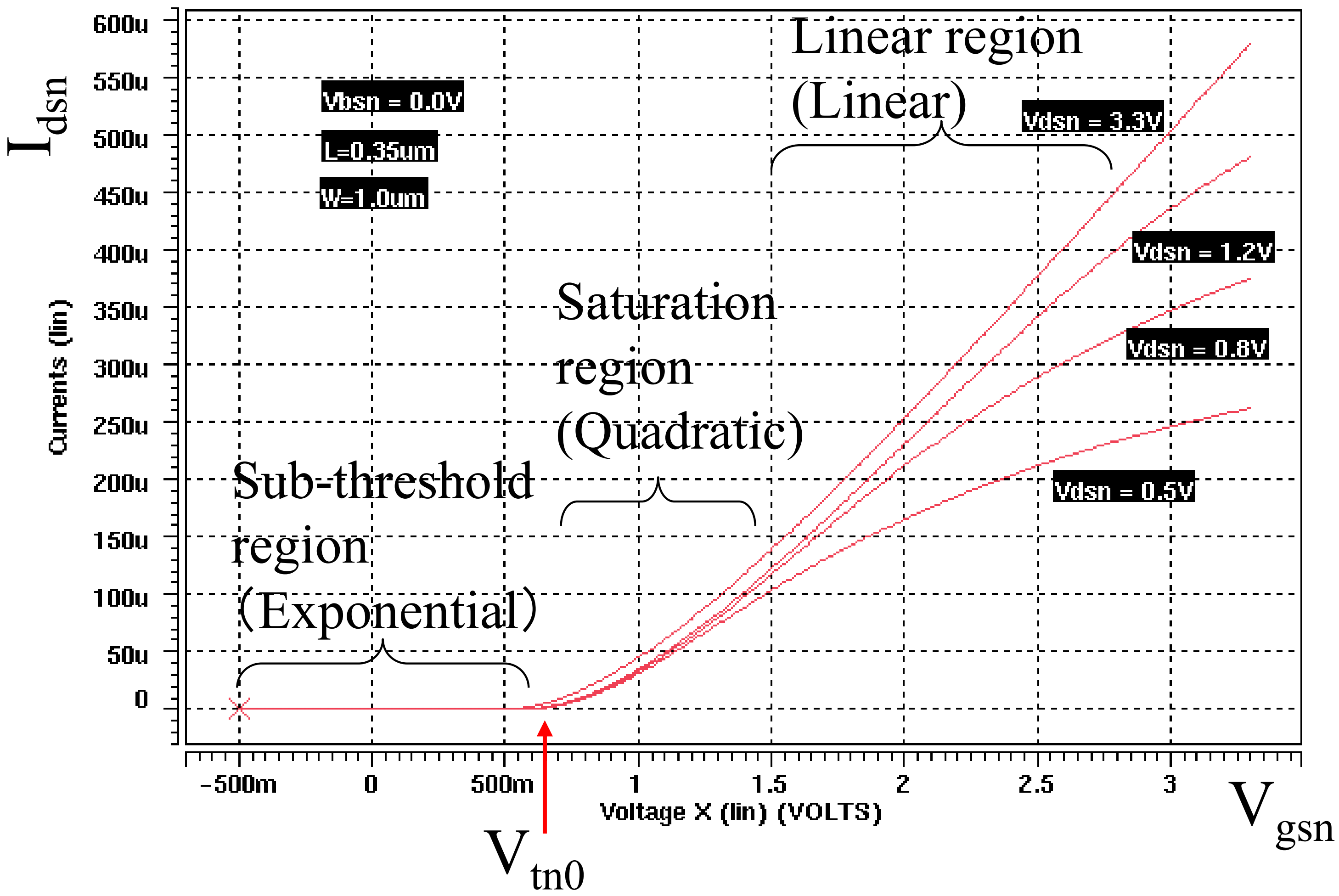
Para-meter	Description	Typical values in 0.5um technology	Responsibility
L	Gate length	0.5um	**Designer**
W	Gate width	> 3um	**Designer**
L_{eff}	Effective gate length	$L_{eff} < L$	Manufacturer
W_{eff}	Effective gate width	$W_{eff} < W$	Manufacturer
x_j	Junction depth	0.2um	Manufacturer
t_{ox}	Thickness of gate oxide	10nm (100Å)	Manufacturer
t_{oxf}	Thickness of field oxide	1um	Manufacturer
t_m	Thickness of gate	0.5um	Manufacturer

Note: Strictly speaking, the electrical characteristics of MOSFET depends on L_{eff}, W_{eff}, and t_{OX}. L_{eff} and W_{eff} can be approximated by L and W, respectively.

I_{ds}-V_{ds} characteristic of MOSFET



I_{ds}-V_{gs} characteristic of MOSFET



Mathematical expression of linear region

Linear region (Gradual Channel Approximation*)

$$I_{dsn} = \frac{W_n}{L_n}\mu_n C_O \{(V_{gsn} - V_{tn0}) \cdot V_{dsn} - \frac{1}{2}V_{dsn}^2\}$$

$$= \beta_n \{(V_{gsn} - V_{tn0}) \cdot V_{dsn} - \frac{1}{2}V_{dsn}^2\} \quad (1)$$

Linear function of V_{gsn} Quadratic function of V_{dsn}

* See appendix for more information.

μ_n: *Electron mobility* (m^2/Vs)

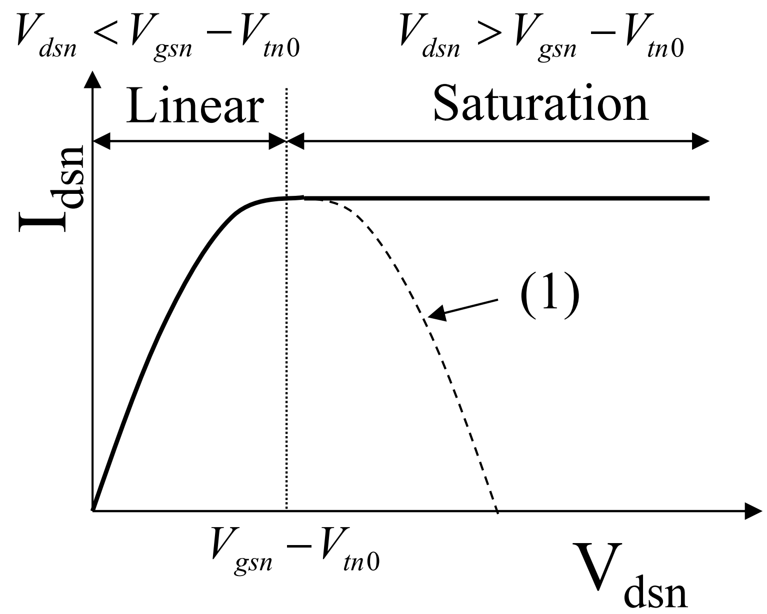
C_O: *Capacitance of a gate oxide* (F/m^2)

V_{tn0}: *Threshold voltage* (V) *at* $V_{sbn} = 0V$

Boundary of the regions

$$\frac{dI_{dsn}}{dV_{dsn}} = \beta_n \{(V_{gsn} - V_{tn0}) - V_{dsn}\} = 0$$ Peak of the curve in linear region

$$V_{dsn} = V_{gsn} - V_{tn0} \quad (2)$$ Boundary of linear region and saturation region (Overdrive voltage)



Mathematical expression of saturation region

Saturation region (Gradual Channel Approximation)

$V_{dsn} = V_{gsn} - V_{tn0} = V_{OV}$ Overdrive voltage

$$I_{dsn} = \beta_n \{(V_{gsn} - V_{tn0}) \cdot (V_{gsn} - V_{tn0}) - \frac{1}{2}(V_{gsn} - V_{tn0})^2\}$$

$$= \frac{\beta_n}{2}(V_{gsn} - V_{tn0})^2 \quad (3)$$

- Quadratic function of V_{gsn}
- Constant for V_{dsn}

4.1.4 Improved model of MOSFET

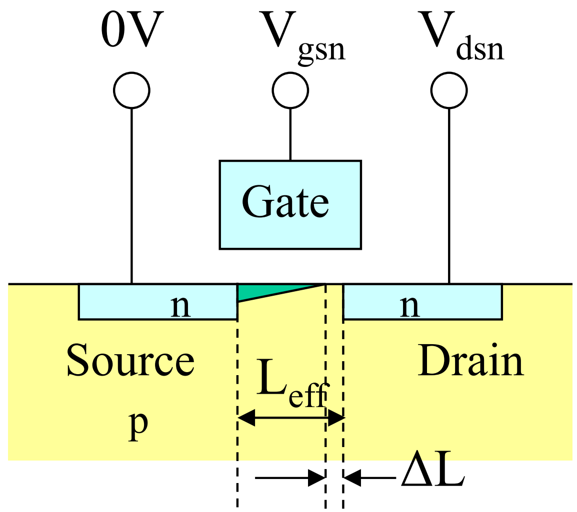
Channel length modulation

$V_{gsn} - V_{dsn} \leq V_{tn0}$ Saturation region

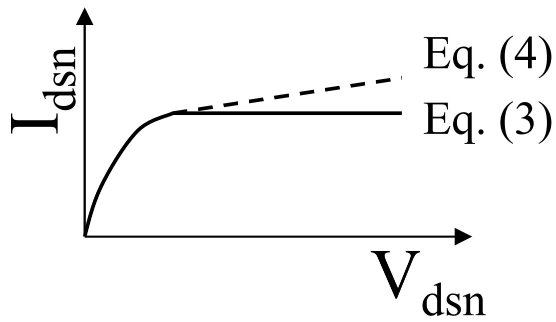
Channel length = $L_{eff} - \Delta L$

(ΔL is proportional to $V_{dsn}^{0.5}$)

The channel length is decreased with increasing V_{dsn} and the I_{dsn} is gradually increased with increasing V_{dsn}.



$$V_{gsn} - V_{dsn} \leq V_{tn0}$$

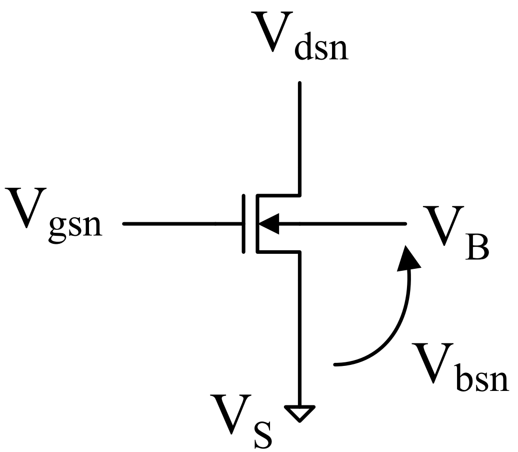


$$I_{dsn} = \underbrace{\frac{\beta_n}{2}\left(V_{gsn} - V_{tn0}\right)^2}_{\text{Eq. (3)}}\{1 + \lambda(V_{dsn} - V_{OV})\} \quad (4)$$

Eq. (3)

↑ λ: Channel length modulation parameter

Body effect 1



MOSFET typically operates under the condition that the body potential V_B = GND potential, but the substrate voltage V_{bsn} is not equal to zero, when the source potential $V_S \neq$ GND potential.

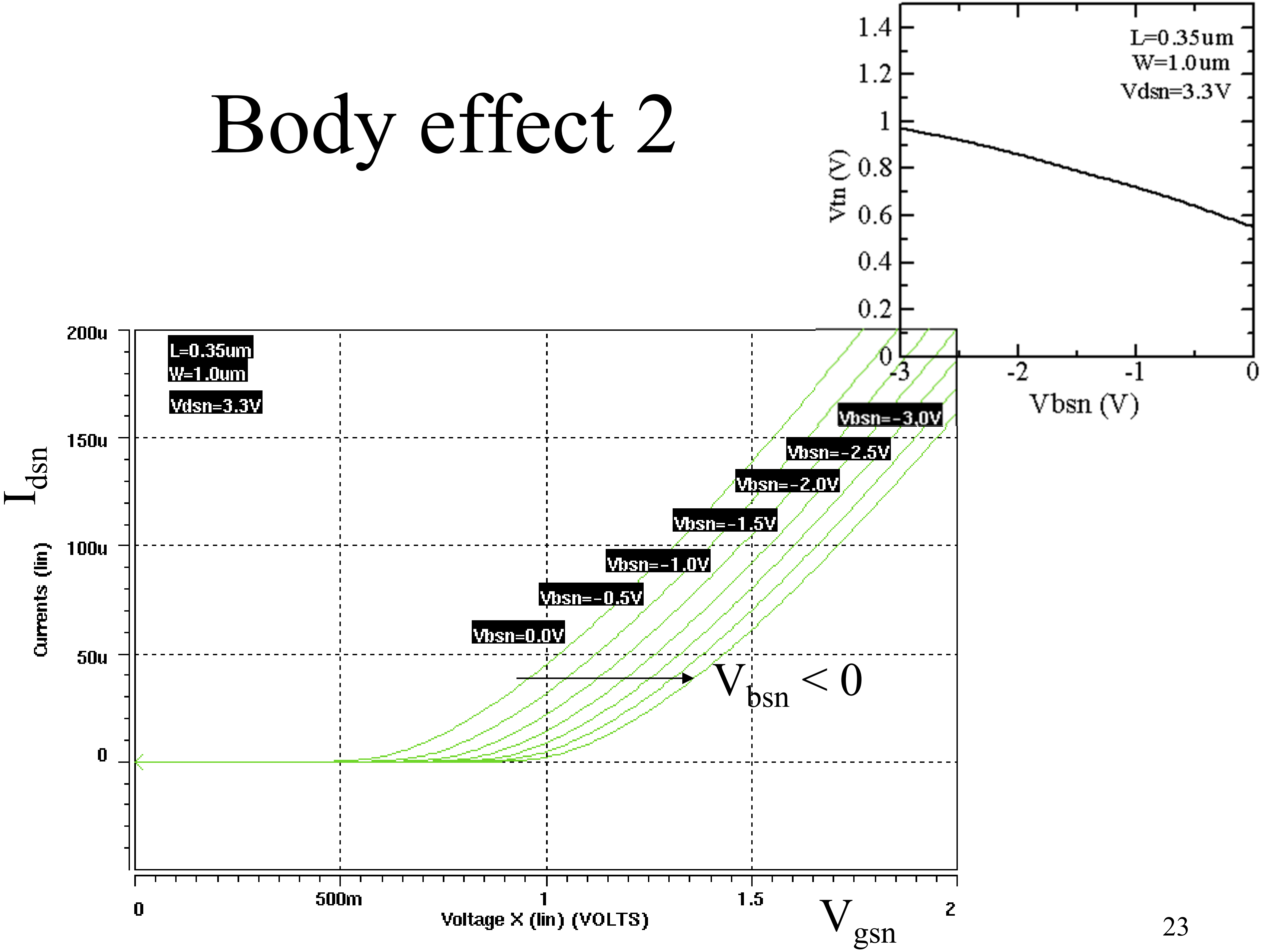
$$V_{tn} = V_{FB} + 2 \cdot \phi_{fp} + \frac{1}{C_O}\sqrt{2 \cdot \varepsilon_r \varepsilon_0 \cdot q \cdot N_A (2 \cdot \phi_{fp} - V_{bsn})} \qquad (5)$$

Impurity concentration in channel region

Substrate voltage

When $V_{bsn} < 0$, The threshold voltage V_{th0} is increased.
(See next slide.)

Body effect 2



Short channel MOSFET

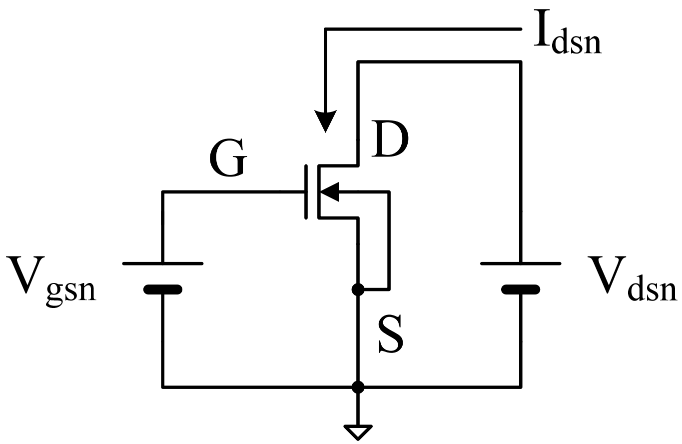
Short channel MOSFET ($L < 0.3\mu m$)

1. Short channel effect
   – A threshold voltages V_{tn0} and $|V_{tp0}|$ are decreased with decreasing a gate length L.
2. Velocity saturation of carrier
   – In a long channel MOSFET, a drift velocity of a carrier is proportional to an electric field. On the other hand, a drift velocity of a carrier is constant in a high electric field of a short channel MOSFET.
   – As the result, I_{ds}-V_{gs} characteristic in a saturation region is not expressed by a quadratic function, but a linear function.

A device model incorporated in circuit simulators takes the short channel effects into account.

4.1.5 Summary of MOSFET model

Summary of n-ch MOSFET model



$$C_O = \varepsilon_0 \varepsilon_{SiO_2} \frac{1}{t_{OX}}$$

Capacitance of a gate oxide (F/m^2)

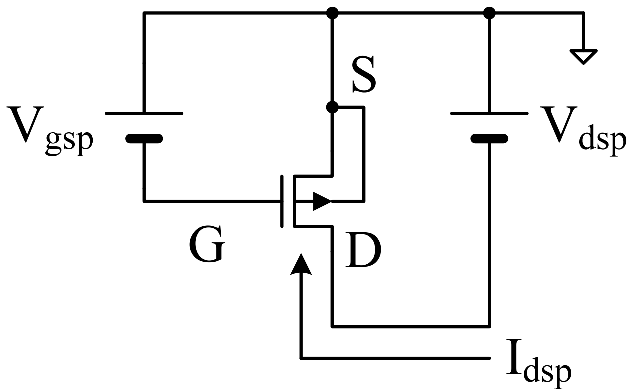
μ_n : Electron mobility (m^2/Vs)

An electron mobility is a material constant.

Region	Model equation
Linear region $V_{dsn} \le V_{gsn} - V_{tn0}$	$I_{dsn} = \beta_n \{(V_{gsn} - V_{tn0}) \cdot V_{dsn} - \frac{1}{2} V_{dsn}^2\}$ $\beta_n = \frac{W_n}{L_n} \mu_n C_O$
Saturation region $V_{dsn} \ge V_{gsn} - V_{tn0}$	$I_{dsn} = \frac{\beta_n}{2} (V_{gsn} - V_{tn0})^2 (1 + \lambda V_{dsn})$ $\approx \frac{\beta_n}{2} (V_{gsn} - V_{tn0})^2$

L_n and W_n are determined by the circuit designer.
C_O is controlled by the semiconductor manufacturer.

Summary of p-ch MOSFET model



$$C_O = \varepsilon_0 \varepsilon_{SiO_2} \frac{1}{t_{OX}}$$

Capacitance of a gate oxide (F/m^2)

μ_n : Electron mobility (m^2/Vs)

An electron mobility is a material constant.

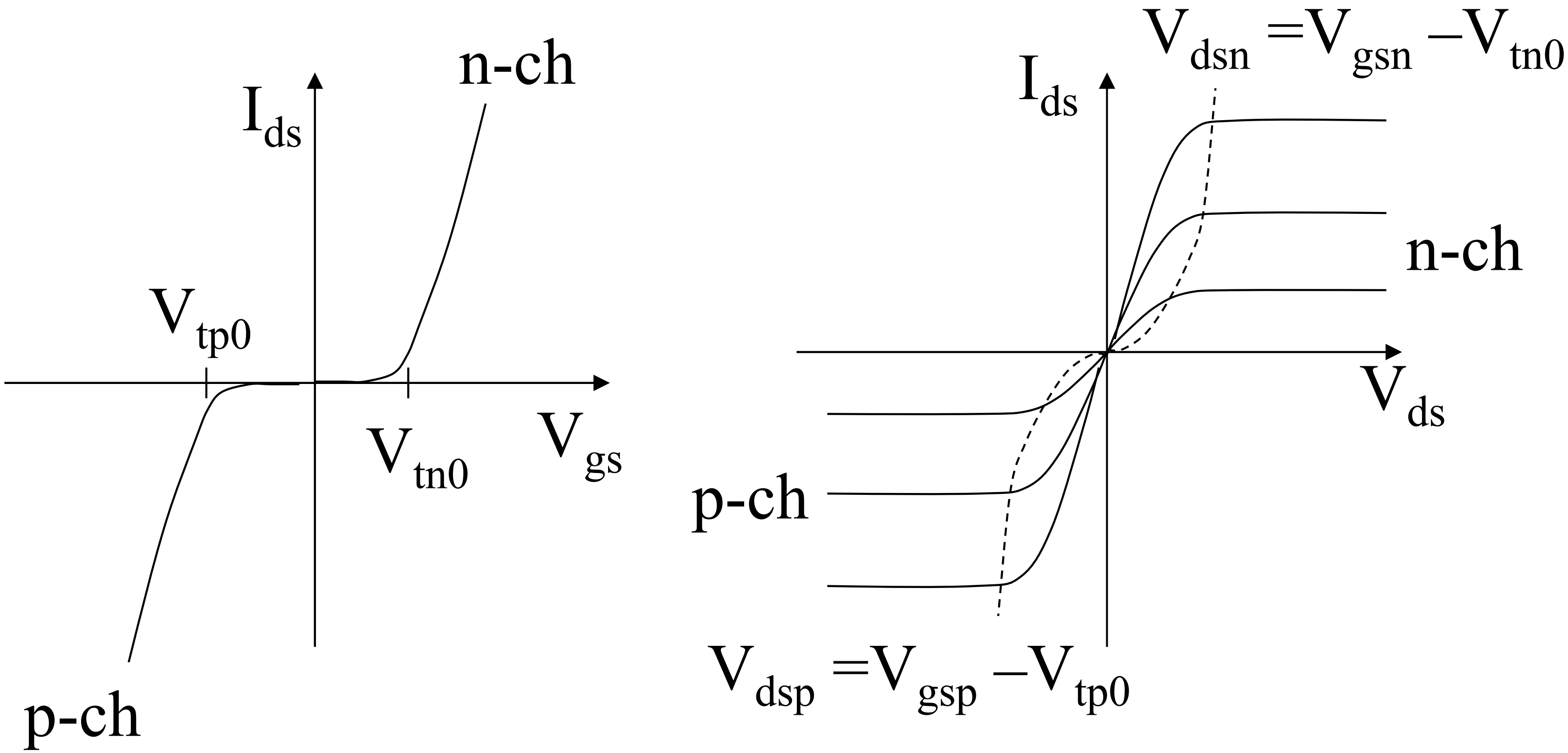
Region	Model equation
Linear region $\lvert V_{dsp} \rvert \le \lvert V_{gsp} - V_{tp0} \rvert$	$I_{dsp} = -\beta_p \{(V_{gsp} - V_{tp0}) \cdot V_{dsp} - \frac{1}{2} V_{dsp}^2\}$ $\beta_p = \frac{W_p}{L_p} \mu_p C_O$
Saturation region $\lvert V_{dsp} \rvert \ge \lvert V_{gsp} - V_{tp0} \rvert$	$I_{dsp} = -\frac{\beta_p}{2} (V_{gsp} - V_{tp0})^2 (1 - \lambda V_{dsp})$ $\approx -\frac{\beta_p}{2} (V_{gsp} - V_{tp0})^2$

Note: V_{gsp}, V_{dsp}, $I_{dsp} < 0$

L_n and W_n are determined by the circuit designer.
C_O is controlled by the semiconductor manufacturer.

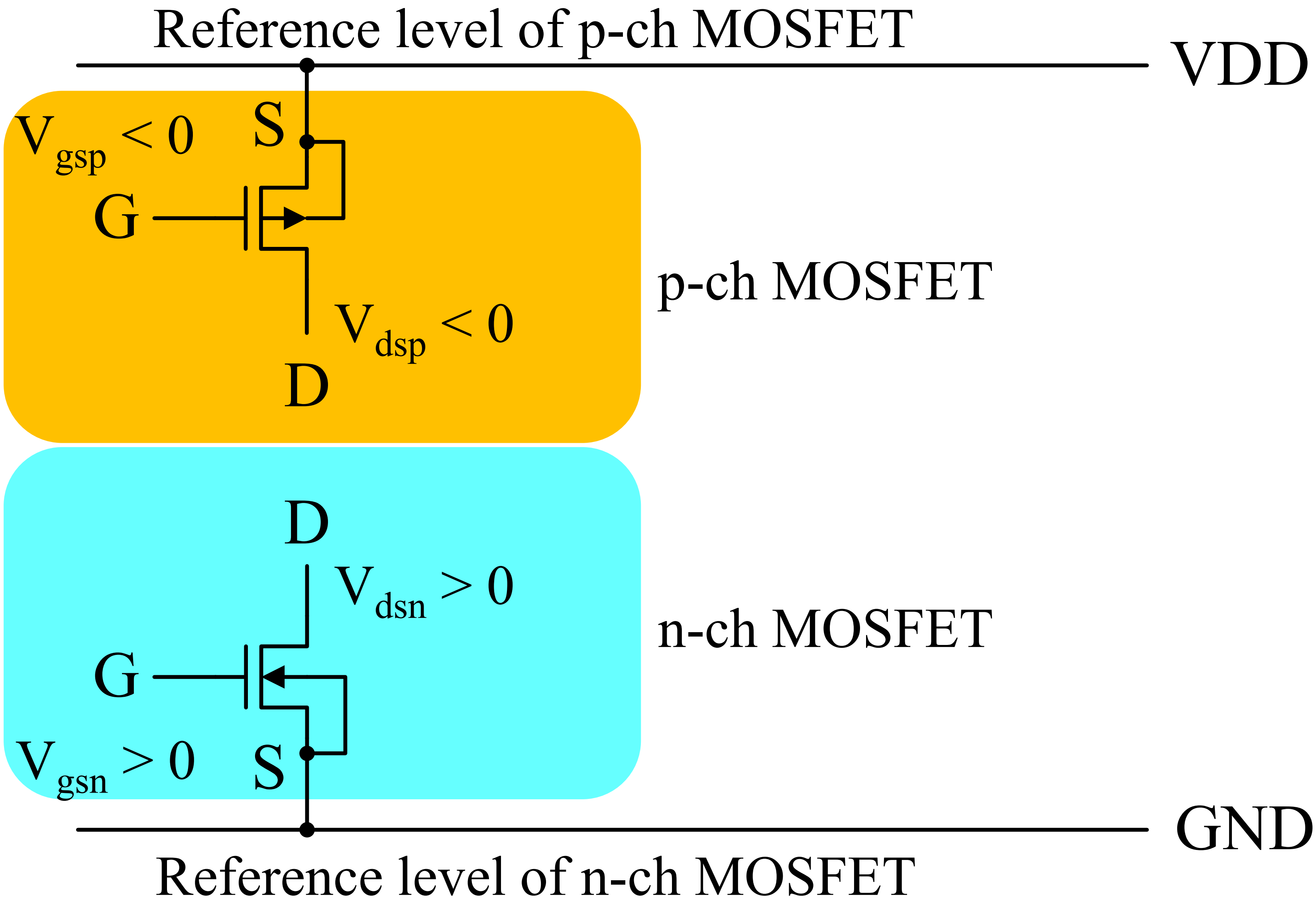
p-ch and n-ch MOSFET

The polarity of the voltage and the current of a p-ch MOSFET and a n-ch MOSFET are opposite each other.



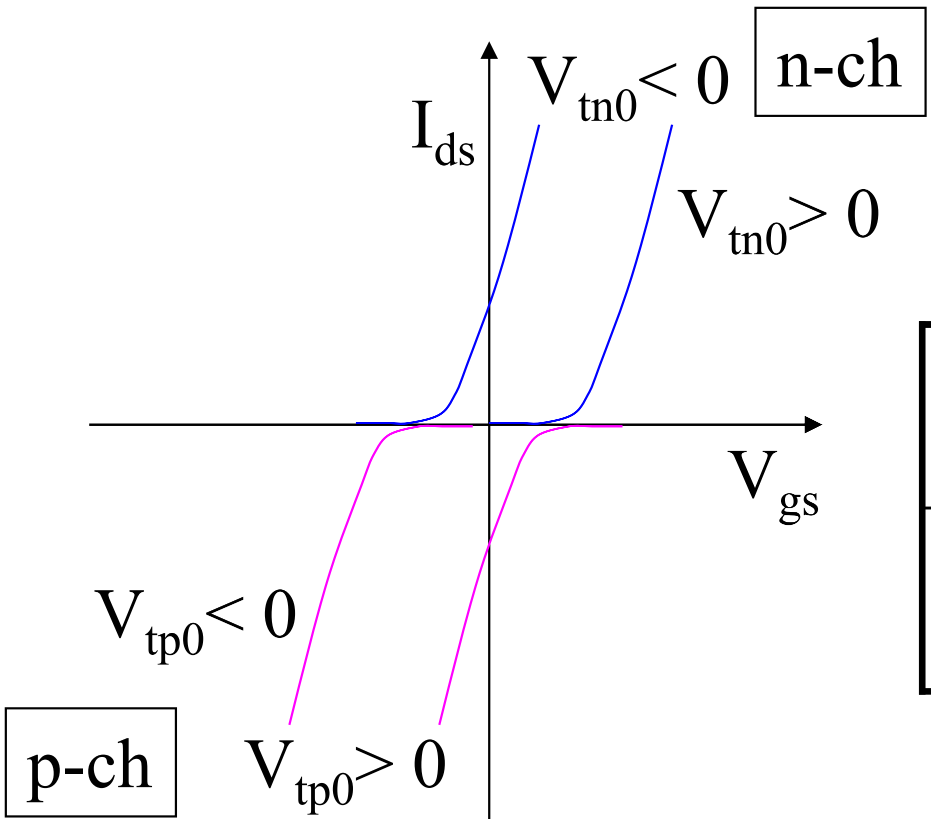
I_{ds}: A current flowing from a drain to a source is positive.

Reference potential of MOSFET



Type of MOSFET

$$V_{tn0} = \frac{\sqrt{2\varepsilon_0 \varepsilon_{Si} q N_A 2\phi_B}}{C_{OX}} + 2\phi_B + V_{FB} = \gamma\sqrt{2\phi_B} + 2\phi_B + V_{FB}$$



The threshold voltage is controlled by V_{FB} (Flat-band voltage) and N_A (Acceptor concentration).

n-ch	$V_{tn0} > 0$	Enhancement mode
	$V_{tn0} < 0$	Depletion mode
p-ch	$V_{tp0} > 0$	Depletion mode
	$V_{tp0} < 0$	Enhancement mode

The enhancement mode MOSFET is used both of logic and analog circuits.