# Basic Transistor Formula

# Table 5.1: Summary of the bipolar current-voltage relationships in the active region

| For npn | For pnp |
|---|---|
| $i_C = I_S e^{v_{BE}/V_T}$ | $i_C = I_S e^{v_{EB}/V_T}$ |
| $i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{BE}/V_T}$ | $i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{EB}/V_T}$ |
| $i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$ | $i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T}$ |

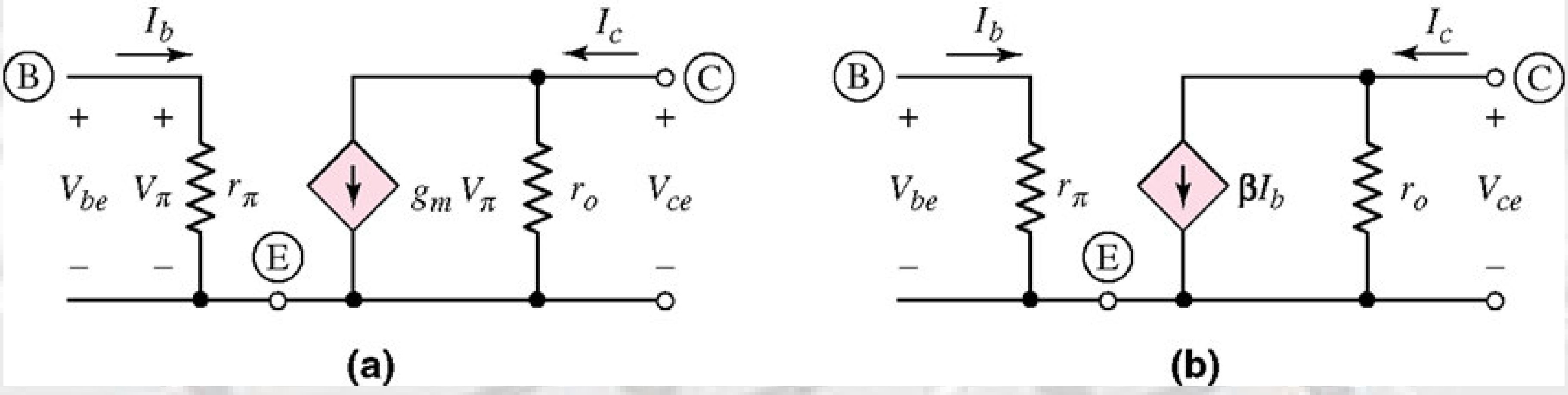
- $I_s$ = Saturation current (strongly dependant on device and temperature
- $V_T$ = Thermal voltage
- $\beta$ = Common-emitter current gain
- $\alpha$ = Common-base current gain

# Table 5.1: Summary of the bipolar current-voltage relationships in the active region (Cont)

| For both transistors |
|---|
| $\alpha = \left(\frac{\beta}{1+\beta}\right); \beta = \left(\frac{\alpha}{1-\alpha}\right)$ |
| $i_C = \beta i_B$ |
| $i_C = \alpha i_E = \left(\frac{\beta}{1+\beta}\right) i_E$ |
| $i_E = i_B + i_C = (1+\beta) i_B$ |

- $\beta$ = Common-emitter current gain
- $\alpha$ = Common-base current gain

# Small-signal Hybrid-*π* Equivalent Circuit of BJT



Expanded small-signal model of the BJT, including the Early effect when the circuit contains the

(a) voltage controlled current source (transconductance)

and (b) current controlled current source (current gain parameters)

**Note:** The small-signal model of a **pnp BJT** is the same as in **figure above** but with all ac voltage polarities and current directions reversed. All the parameter equations stated **next** still apply for the **pnp** transistor.

# Small-signal Hybrid-$\pi$ Equivalent Circuit of BJT (Cont)

| | |
|---|---|
| • Diffusion resistance: | $r_\pi = \left[\frac{\partial i_B}{\partial v_{BE}}\Big\|_{Q-pt}\right]^{-1} = \frac{\beta V_T}{I_{CQ}}$ |
| • Transconductance: | $g_m = \left[\frac{\partial i_C}{\partial v_{BE}}\Big\|_{Q-pt}\right] = \frac{I_{CQ}}{V_T}$ |
| • ac common-emitter current gain: | $\beta = \left[\frac{\partial i_C}{\partial i_B}\Big\|_{Q-pt}\right] = g_m r_\pi$ |
| • Small-signal transistor output resistance: | $r_o = \left[\frac{\partial i_C}{\partial v_{CE}}\Big\|_{Q-pt}\right]^{-1} = \frac{V_A}{I_{CQ}}$ |

# Current-voltage Relationships for MOSFET

| Region | NMOS | PMOS |
|---|---|---|
| Non-saturation | $v_{DS} < v_{DS}$(sat)<br>$i_D = K_n[2(v_{GS} - V_{TN})v_{DS} - v_{DS}^2]$ | $v_{SD} < v_{SD}$(sat)<br>$i_D = K_p[2(v_{SG} + V_{TP})v_{SD} - v_{SD}^2]$ |
| Saturation | $v_{DS} \geq v_{DS}$(sat)<br>$i_D = K_n[v_{GS} - V_{TN}]^2$ | $v_{SD} \geq v_{SD}$(sat)<br>$i_D = K_p[v_{SG} + V_{TP}]^2$ |
| Transition Point | $v_{DS}$(sat) = $v_{GS}$ - $V_{TN}$ | $v_{SD}$(sat) = $v_{SG}$ + $V_{TP}$ |
| Enhancement Mode | $V_{TN} >$ 0V | $V_{TP} <$ 0V |
| Depletion Mode | $V_{TN} <$ 0V | $V_{TP} >$ 0V |

# Current-voltage Relationships for MOSFET (Cont)

## Conduction Parameters

- NMOSFET: $$K_n = \frac{W\mu_n C_{ox}}{2L} = \frac{k_n^{'}}{2} \cdot \frac{W}{L}$$
- PMOSFET: $$K_p = \frac{W\mu_p C_{ox}}{2L} = \frac{k_p^{'}}{2} \cdot \frac{W}{L}$$

where: $$C_{ox} = \varepsilon_{ox} / t_{ox}$$

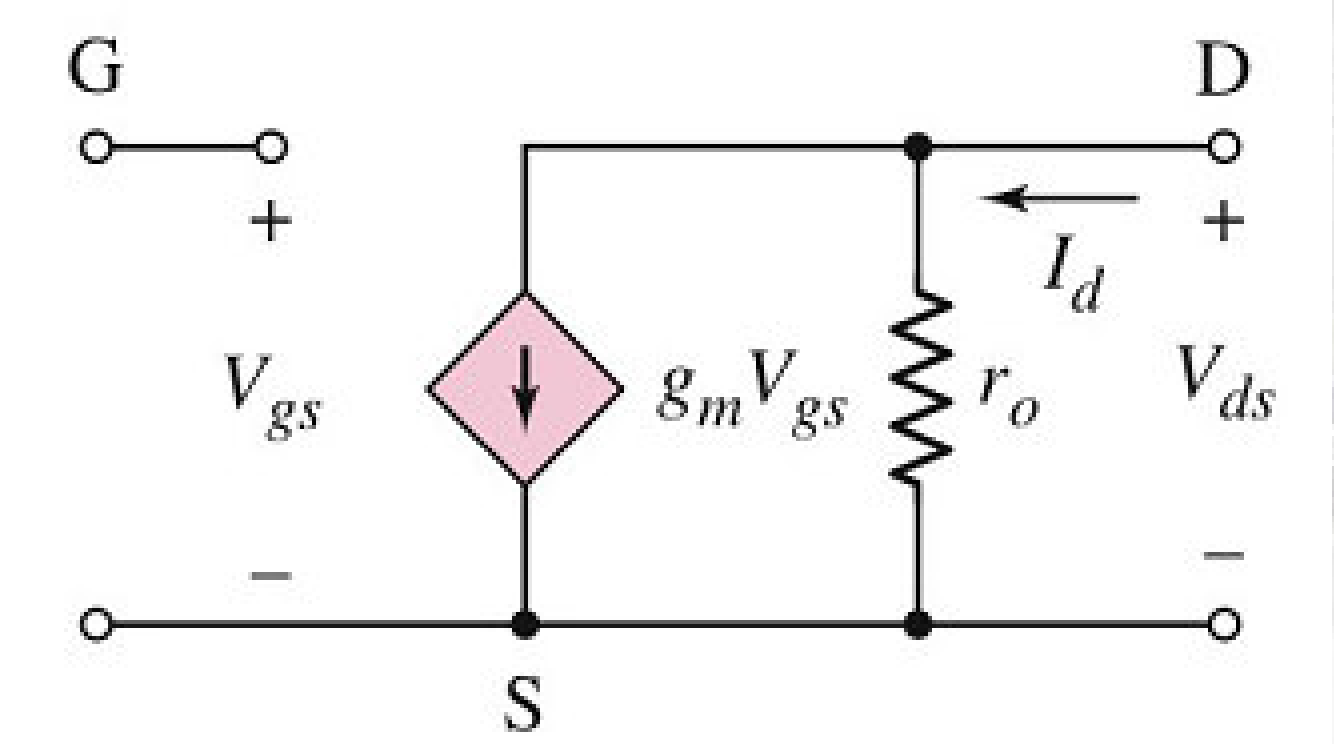
is the oxide capacitance per unit area

# Current-voltage Relationships of MOSFET (Cont)

| | |
|---|---|
| $\mu_n$ | mobility of electrons |
| $\mu_p$ | mobility of holes |
| $\varepsilon_{ox}$ | oxide permittivity |
| $t_{ox}$ | oxide **t**hickness |
| $W$ | channel **W**idth |
| $L$ | channel **L**ength |
| $k_n' = \mu_n C_{ox}$ | process conduction parameter (provided by manufacturer for a particular process) |

➔ The channel geometry, i.e. **width-to-length ratio ($W/L$)**, is a variable in the design of MOSFETs that **can be utilized to produce specific current-voltage characteristics** in MOSFET circuits.

# Small-signal Hybrid-π Equivalent Circuit of MOSFET



Expanded small-signal equivalent circuit,
including output resistance,
for NMOS transistor.

## Small-signal Hybrid-π Equivalent Circuit of MOSFET (Cont)

- **Transconductance:**

$$g_m = \frac{\partial i_D}{\partial v_{GS}} \Big|_{v_{GS}=V_{GSQ}=const} = 2K_n\left(V_{GSQ} - V_{TN}\right) = 2\sqrt{K_n I_{DQ}}$$

- **Small-signal transistor output resistance:**

$$r_o = \left[\frac{\partial i_D}{\partial v_{DS}}\right]^{-1} \Big|_{v_{GS}=V_{GSQ}=const} = \left[\lambda K_n\left(V_{GSQ} - V_{TN}\right)^2\right]^{-1} \cong \left[\lambda I_{DQ}\right]^{-1}$$

Note: The small-signal model of a PMOS transistor is the same as in previous figure but with all ac voltage polarities and current directions reversed. All the parameter equations **stated above** still apply for the PMOS transistor.

# Finite Output Resistance

This effect is included in the drain current equation:

$$i_D = K_n \left[ \left( v_{GS} - V_{TN} \right)^2 \left( 1 + \lambda v_{DS} \right) \right]$$

Output resistance,

$$r_o = \left[ \frac{\partial i_D}{\partial v_{DS}} \right]^{-1} \Big|_{v_{GS}=const} \cong \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$$

where $I_{DQ}$ = quiescent drain current.

Note: $V_A$ is analogous to Early voltage of a BJT.