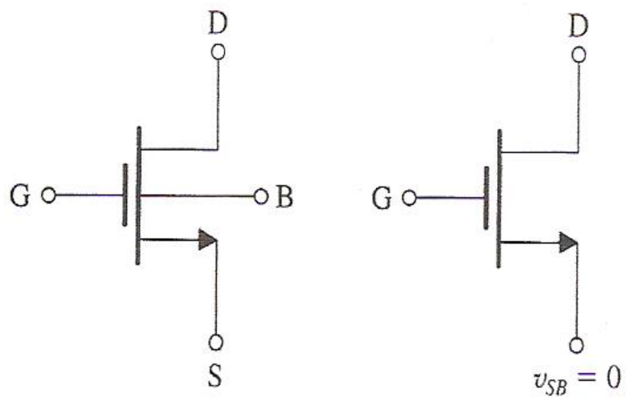
TABLE 4.1 Summary of the MOSFET Current-Voltage Characteristics

NMOS Transistor

Symbol:



Overdrive voltage:

$$v_{OV} = v_{GS} - V_t$$

$$v_{GS} = V_t + v_{OV}$$

Operation in the *triode* region:

- Conditions:

(1) $v_{GS} \geq V_t \quad \Leftrightarrow \quad v_{OV} \geq 0$

(2) $v_{GD} \geq V_t \quad \Leftrightarrow \quad v_{DS} \leq v_{GS} - V_t \quad \Leftrightarrow \quad v_{DS} \leq v_{OV}$

- i-v Characteristics:

$$i_D = \mu_n C_{ox} \frac{W}{L}\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

- For $v_{DS} \ll 2(v_{GS} - V_t) \quad \Leftrightarrow \quad v_{DS} \ll 2v_{OV}$

$$r_{DS} \equiv \frac{v_{DS}}{i_D} = 1\Big/\left[\mu_n C_{ox} \frac{W}{L}(v_{GS} - V_t)\right]$$

Operation in the *saturation* region:

- Conditions:

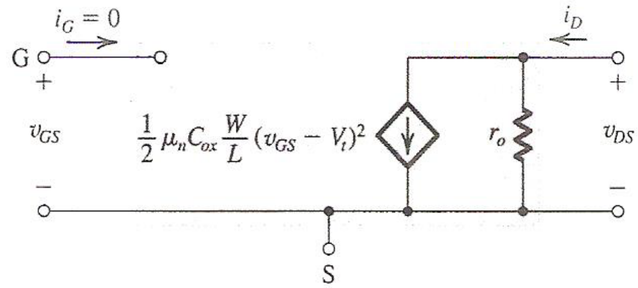
(1) $v_{GS} \geq V_t \quad \Leftrightarrow \quad v_{OV} \geq 0$

(2) $v_{GD} \leq V_t \quad \Leftrightarrow \quad v_{DS} \geq v_{GS} - V_t \quad \Leftrightarrow \quad v_{DS} \geq v_{OV}$

- i-v Characteristics:

$$i_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(v_{GS} - V_t)^2(1 + \lambda v_{DS})$$

- Large-signal equivalent circuit model:



$$r_o = \left[\lambda \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)^2\right]^{-1} = \frac{V_A}{I_D}$$

where

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)^2$$

Threshold voltage:

$$V_t = V_{t0} + \gamma(\sqrt{2\phi_f + |V_{SB}|} - \sqrt{2\phi_f})$$

Process parameters:

$C_{ox} = \varepsilon_{ox}/t_{ox}$	$(\mathrm{F/m^2})$
$k_n' = \mu_n C_{ox}$	$(\mathrm{A/V^2})$
$V_A' = (V_A/L)$	$(\mathrm{V/m})$
$\lambda = (1/V_A)$	$(\mathrm{V^{-1}})$
$\gamma = \sqrt{2qN_A\varepsilon_s}/C_{ox}$	$(\mathrm{V^{1/2}})$

Constants:

$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

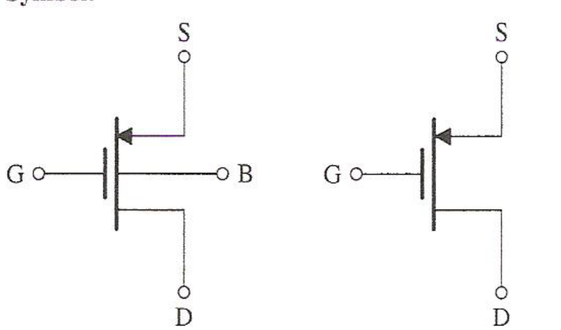
$\varepsilon_{ox} = 3.9\varepsilon_0 = 3.45 \times 10^{-11}$ F/m

$\varepsilon_s = 11.7\varepsilon_0 = 1.04 \times 10^{-10}$ F/m

$q = 1.602 \times 10^{-19}$ C

PMOS Transistor

Symbol:



$v_{SB} = 0$

Overdrive voltage:

$$v_{OV} = v_{GS} - V_t$$

$$v_{SG} = |V_t| + |v_{OV}|$$

TABLE 4.1 *(Continued)*

***i-v* Characteristics:**

Same relationships as for NMOS transistors except:

- Replace μ_n, k_n', and N_A with μ_p, k_p', and N_D, respectively.
- V_t, V_{t0}, V_A, λ, and γ are negative.
- Conditions for operation in the **triode** region:

  (1) $v_{GS} \le V_t \quad \Leftrightarrow \quad v_{OV} \le 0 \quad \Leftrightarrow \quad v_{SG} \ge |V_t|$

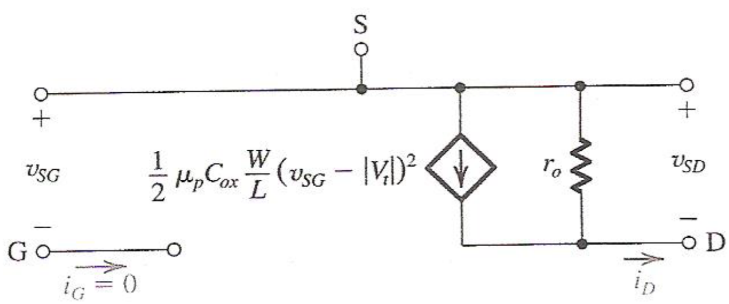
  (2) $v_{DG} \ge |V_t| \quad \Leftrightarrow \quad v_{DS} \ge v_{GS} - V_t \quad \Leftrightarrow \quad v_{SD} \le |v_{OV}|$

- Conditions for operation in the **saturation** region:

  (1) $v_{GS} \le V_t \quad \Leftrightarrow \quad v_{OV} \le 0 \quad \Leftrightarrow \quad v_{SG} \ge |V_t|$

  (2) $v_{DG} \le |V_t| \quad \Leftrightarrow \quad v_{DS} \le v_{GS} - V_t \quad \Leftrightarrow \quad v_{SD} \ge |v_{OV}|$

- Large-signal equivalent circuit model:



$$r_o = \left[|\lambda|\frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{SG}-|V_t|)^2\right]^{-1} = \frac{|V_A|}{I_D}$$

where

$$I_D = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}(V_{SG}-|V_t|^2)$$

TABLE 4.2 Small-Signal Equivalent-Circuit Models for the MOSFET

Small-Signal Parameters

NMOS transistors:

- Transconductance:

$$g_m = \mu_n C_{ox} \frac{W}{L} V_{OV} = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} = \frac{2I_D}{V_{OV}}$$

- Output resistance:

$$r_o = V_A / I_D = 1/\lambda I_D$$

- Body transconductance:

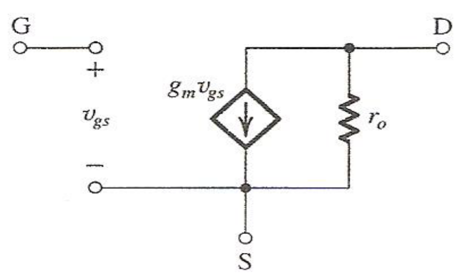
$$g_{mb} = \chi g_m = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} g_m$$

PMOS transistors:

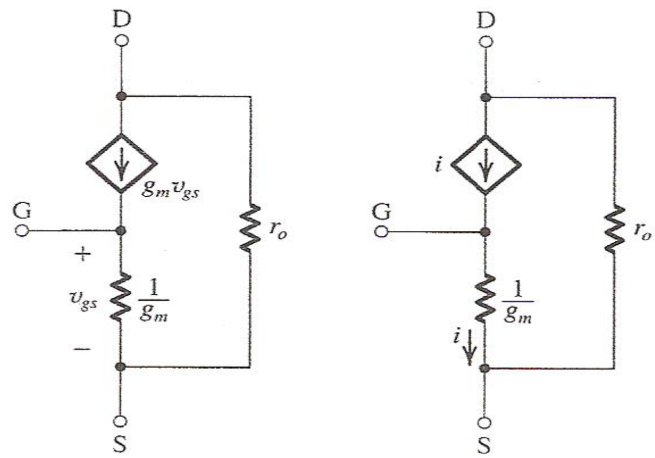
Same formulas as for NMOS *except* using $|V_{OV}|$, $|V_A|$, $|\lambda|$, $|\gamma|$, $|V_{SB}|$, and $|\chi|$ and replacing μ_n with μ_p.

TABLE 4.2 *(Continued)*

Small-Signal Equivalent Circuit Models when $|V_{SB}| = 0$ (i.e., No Body Effect)

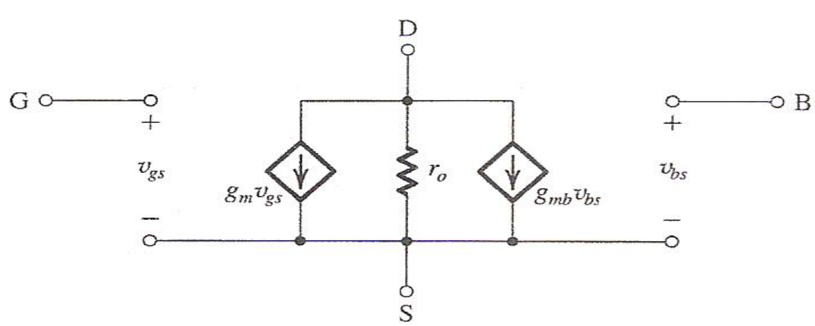


Hybrid-π model



T models

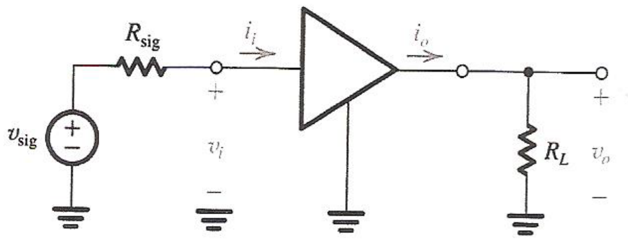
Small-Signal Circuit Model when $|V_{SB}| \neq 0$ (i.e., Including the Body Effect)



Hybrid-π model

TABLE 4.3 Characteristic Parameters of Amplifiers

Circuit



Definitions

- Input resistance with no load:

$$R_i \equiv \left.\frac{v_i}{i_i}\right|_{R_L=\infty}$$

- Input resistance:

$$R_{in} \equiv \frac{v_i}{i_i}$$

- Open-circuit voltage gain:

$$A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{R_L=\infty}$$

- Voltage gain:

$$A_v \equiv \frac{v_o}{v_i}$$

- Short-circuit current gain:

$$A_{is} \equiv \left.\frac{i_o}{i_i}\right|_{R_L=0}$$

- Current gain:

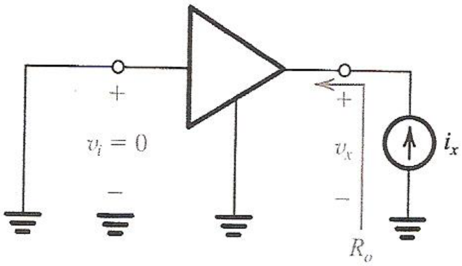
$$A_i \equiv \frac{i_o}{i_i}$$

- Short-circuit transconductance:

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0}$$

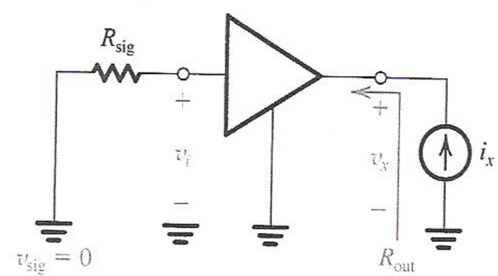
- Output resistance of amplifier proper:

$$R_o \equiv \left.\frac{v_x}{i_x}\right|_{v_i=0}$$



- Output resistance:

$$R_{out} \equiv \left.\frac{v_x}{i_x}\right|_{v_{sig}=0}$$



- Open-circuit overall voltage gain:

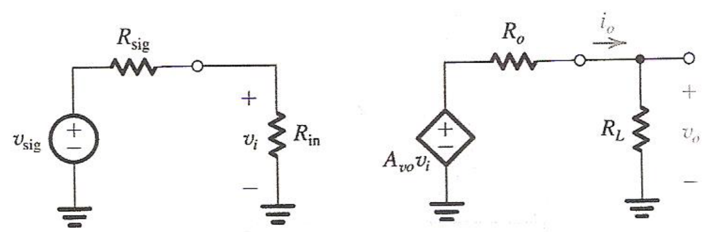
$$G_{vo} \equiv \left.\frac{v_o}{v_{sig}}\right|_{R_L=\infty}$$

- Overall voltage gain:

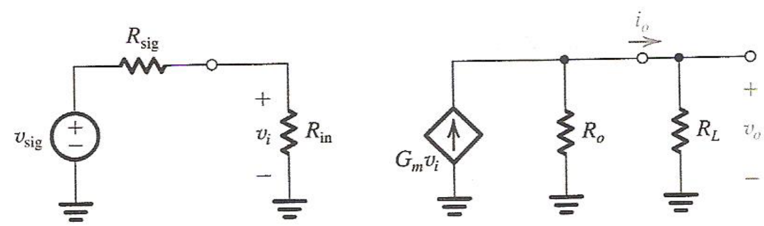
$$G_v \equiv \frac{v_o}{v_{sig}}$$

Equivalent Circuits

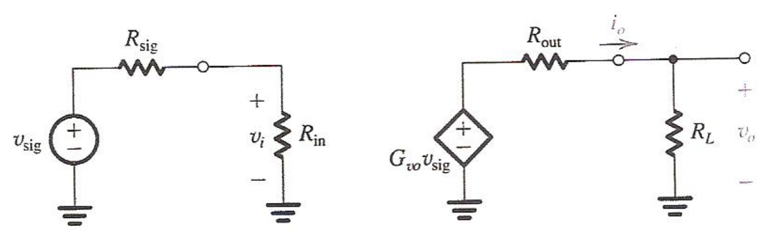
- A:



- B:



- C:

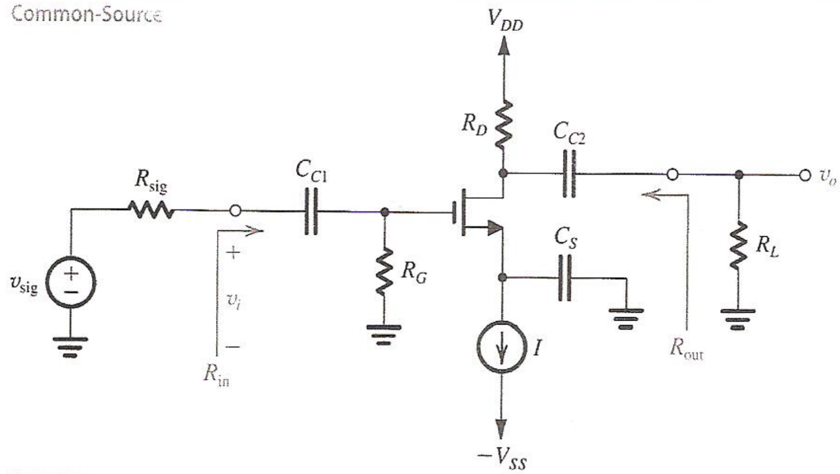


Relationships

- $\frac{v_i}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}}$
- $A_v = A_{vo}\frac{R_L}{R_L + R_o}$
- $A_{vo} = G_m R_o$
- $G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_{vo} \frac{R_L}{R_L + R_o}$
- $G_{vo} = \frac{R_i}{R_i + R_{sig}} A_{vo}$
- $G_v = G_{vo} \frac{R_L}{R_L + R_{out}}$

TABLE 4.4 **Characteristics of Single-Stage Discrete MOS Amplifiers**

Common-Source



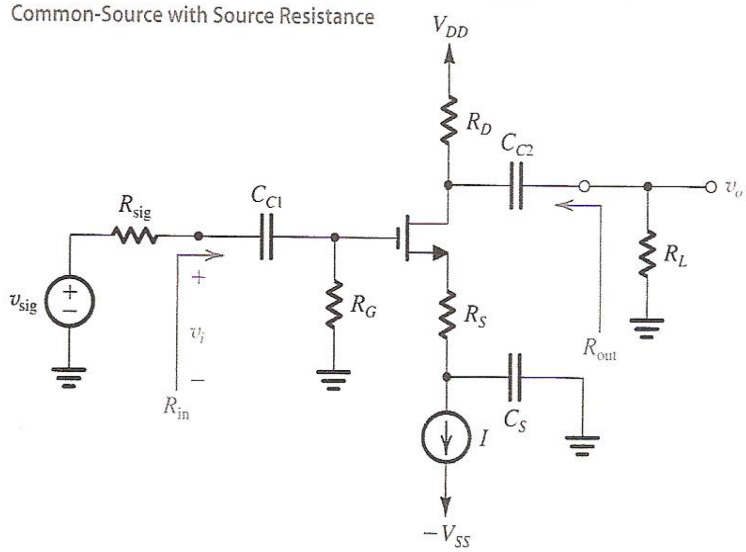
$$R_{in} = R_G$$

$$A_v = -g_m(r_o \,\|\, R_D \,\|\, R_L)$$

$$R_{out} = r_o \,\|\, R_D$$

$$G_v = -\frac{R_G}{R_G + R_{sig}} g_m(r_o \,\|\, R_D \,\|\, R_L)$$

Common-Source with Source Resistance



Neglecting r_o:

$$R_{in} = R_G$$

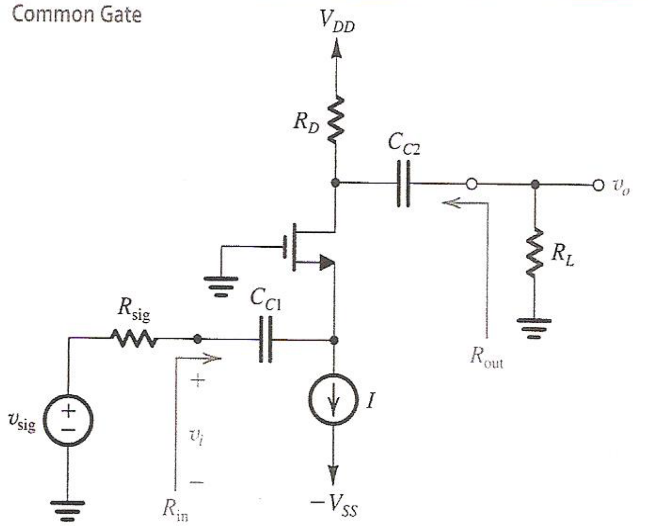
$$A_v = -\frac{R_D \,\|\, R_L}{\dfrac{1}{g_m} + R_S} = -\frac{g_m(R_D \,\|\, R_L)}{1 + g_m R_S}$$

$$R_{out} = R_D$$

$$G_v = -\frac{R_G}{R_G + R_{sig}} \frac{g_m(R_D \,\|\, R_L)}{1 + g_m R_S}$$

$$\frac{v_{gs}}{v_i} = \frac{1}{1 + g_m R_S}$$

Common Gate



Neglecting r_o:

$$R_{in} = \frac{1}{g_m}$$

$$A_v = g_m(R_D \,\|\, R_L)$$

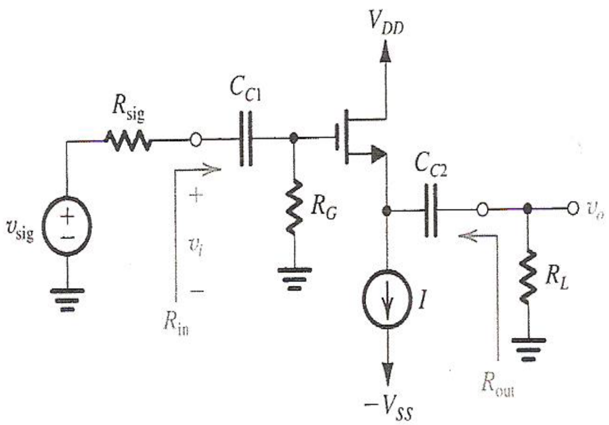
$$R_{out} = R_D$$

$$G_v = \frac{1}{1 + g_m R_{sig}} g_m(R_D \,\|\, R_L)$$

(Continued)

TABLE 4.4 ***(Continued)***

Common-Drain or Source Follower



$$R_{in} = R_G$$

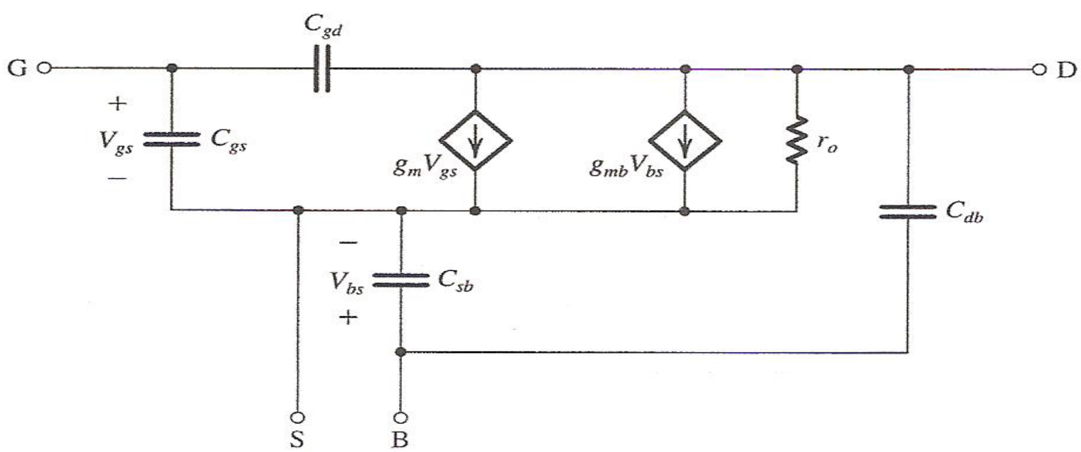
$$A_v = \frac{r_o \parallel R_L}{(r_o \parallel R_L) + \frac{1}{g_m}}$$

$$R_{out} = r_o \parallel \frac{1}{g_m} \cong \frac{1}{g_m}$$

$$G_v = \frac{R_G}{R_G + R_{sig}} \frac{r_o \parallel R_L}{(r_o \parallel R_L) + \frac{1}{g_m}}$$

TABLE 4.5 **The MOSFET High-Frequency Model**

Model



Model Parameters

$$g_m = \mu_n C_{ox}\frac{W}{L}V_{OV} = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D} = \frac{2I_D}{V_{OV}}$$

$$g_{mb} = \chi g_m = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}g_m$$

$$r_o = V_A/I_D$$

$$C_{gs} = \tfrac{2}{3}WLC_{ox} + WL_{ov}C_{ox}$$

$$C_{gd} = WL_{ov}C_{ox}$$

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1+\frac{V_{SB}}{V_0}}}$$

$$C_{db} = \frac{C_{db0}}{\sqrt{1+\frac{V_{DB}}{V_0}}}$$

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

TABLE 4.6 Summary of Important Characteristics of the CMOS Logic Inverter

Gate Output Resistance

- When v_O is low (current sinking) (Fig. 4.54):

$$r_{DSN} = 1\Big/\left[k_n'\left(\frac{W}{L}\right)_n(V_{DD}-V_{tn})\right]$$

- When v_O is high (current sourcing) (Fig. 4.55):

$$r_{DSP} = 1\Big/\left[k_p'\left(\frac{W}{L}\right)_p(V_{DD}-|V_{tp}|)\right]$$

Gate Threshold Voltage

Point on VTC at which $v_O = v_I$:

$$V_{th} = \frac{r(V_{DD}-|V_{tp}|)+V_{tn}}{1+r}$$

where

$$r = \sqrt{\frac{k_p'(W/L)_p}{k_n'(W/L)_n}}$$

Switching Current and Power Dissipation (Fig. 4.58)

$$I_{\text{peak}} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_n\left(\frac{V_{DD}}{2}-V_{tn}\right)^2$$

$$P_D = fCV_{DD}^2$$

Noise Margins (Fig. 4.56)

For matched devices, that is, $\mu_n\left(\frac{W}{L}\right)_n = \mu_p\left(\frac{W}{L}\right)_p$:

$$V_{th} = V_{DD}/2$$

$$V_{IL} = \tfrac{1}{8}(3V_{DD}+2V_t)$$

$$V_{IH} = \tfrac{1}{8}(5V_{DD}-2V_t)$$

$$NM_H = NM_L = \tfrac{1}{8}(3V_{DD}+2V_t)$$

Propagation Delay (Fig. 4.57)

For $V_t \cong 0.2V_{DD}$:

$$t_{PHL} \cong \frac{1.6C}{k_n'(W/L)_nV_{DD}}$$

$$t_{PLH} \cong \frac{1.6C}{k_p'(W/L)_pV_{DD}}$$