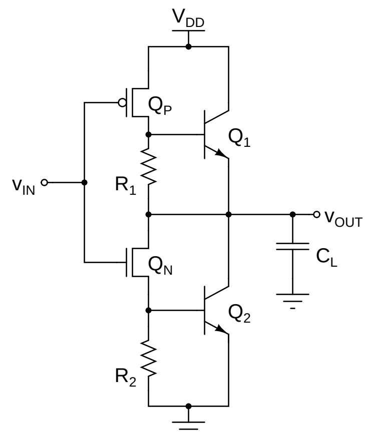
BiCMOS Logic

INEL4207 - M. Toledo

Example

For the BiCMOS gate shown in the following diagram,



use the average current method to estimate

1. the *rise time*[1] t_r,
2. the *fall time*[2] t_f, and
3. t_{PLH}

if $C_L = 1pF$, $\beta = 100$, $\mu_n C_{ox} = 4\mu_p C_{ox} = 0.3mA/V^2$, $V_{tn} = -V_{tp} = 0.5V$ and $v_{BE} = 0.7V$ for transistors that are ON. Neglect the body effect. Use $V_{DD} = 3V$, $W/L = 1$ for both FETs, and $R_1 = R_2 = 20k\Omega$.

ANSWER:

1. To find t_r, consider $v_{IN} = 0V$, and the two conditions when $v_{OUT} = 0.1 \times 3V = 0.3V$ and $v_{OUT} = 0.9 \times 3V = 2.7V$.

   On the first case there is enough voltage difference from the power supply to the output to provide Q_1 with a base-to-emitter voltage of $0.7V$, and the transistor is ON.

[1] t_r is the time it takes for v_{OUT} to go from 10 % to 90 % of V_{DD}
[2] t_f is the time it takes for v_{OUT} to go from 90 % to 10 % of V_{DD}

Therefore the capacitor charging current is given by

$$\begin{aligned} i_{cap,1} &= i_{e1} + i_{R_1} = \beta i_{b1} + i_{R_1} \\ &= \beta \left(i_{DP} - i_{R_1} \right) + i_{R_1} \\ &= \beta i_{DP} - (\beta - 1) \frac{0.7V}{R_1} \end{aligned}$$

Since $v_{SD,P} = 3V - 0.7V - 0.3V = 2.0V < v_{SG,P} + V_{tp} = 3V - 0V - 0.5V = 2.5V$, the pmosfet is operating in triode mode. Thus

$$i_{D,P} = \frac{1}{2} \frac{0.3mA/V^2}{4} \left(2\,(2.5V)\,2V - (2V)^2 \right) = 0.225mA$$

and

$$i_{cap,1} = 100(0.225mA) - (99) \frac{0.7V}{20k\Omega} = 22.5mA - 3.465mA = 19.035mA$$

For the second case the voltage difference between supply and output is only $0.3V$ and the transistor will be OFF. The capacitor current will be flowing through the Q_P and R_1. To find the current, consider the current equation

$$i_{D,P} = \frac{1}{2} \frac{0.3mA/V^2}{4} \left(2\,(2.5V)\,v_{SD,P} - v_{SD,P}^2 \right) = 37.5\mu A/V^2 \left(5v_{SD,P} - v_{SD,P}^2 \right)$$

and

$$V_{DD} - v_{OUT} = 0.3V = v_{SD,P} + 20k\Omega \times i_{D,P}$$

These equations will have to be satisfied simultaneously. Solving the second equation for $i_{D,P}$, substituting into the first equation and rearranging, one obtains

$$0.3V - v_{SD,P} = 0.75V^{-1} \left((5V) v_{SD,P} - v_{SD,P}^2 \right)$$

which can be solved to get $v_{DS,P} = 63.8mV$ and $i_{D,P} = 11.81\mu A = i_{cap,2}$. The small magnitude of this current indicates that once the transistor turns off, the capacitor charges at a considerably slower speed.

The average current is $\frac{19.035mA + 0.01181mA}{2} = 9.52mA$ and

$$t_r \simeq 1pF \frac{2.7V - 0.3V}{9.52mA} = \boxed{252ps}$$

2. <u>To find t_f</u>, consider $v_{IN} = 3V$, and the two conditions when $v_{OUT} = 0.9 \times 3V = 2.7V$ and $v_{OUT} = 0.1 \times 3V = 0.3V$.

   When $v_{OUT} = 2.7V$, Q_2 will be ON and $v_{BE,2} = 0.7V$. Thus

$$i_{cap,3} = i_{c,2} + i_{D,N} = \beta \left(i_{D,N} - \frac{0.7V}{20k\Omega} \right) + i_{D,N} = 101 i_{D,N} - 3.5mA$$

   For Q_N, $v_{DS,N} = 2.7V - 0.7V = 2V > v_{GS,N} - V_{tn} = 3V - 0.7V - 0.5V = 1.8V$ so the NMOS is saturated and

$$i_{D,N} = \frac{0.3mA/V^2}{2} (1.8V)^2 = 486\mu A$$

and

$$i_{cap,3} = 101(0.486mA) - 3.5mA = 45.586mA$$

When $v_{OUT} = 0.3V$, Q_2 will be OFF. The NMOS transistor will operate in triode mode with $v_{GS,N} = 3V - 20k\Omega \times i_{D,N}$ and $v_{DS,N} = 0.3V - 20k\Omega \times i_{D,N}$. The current equation is

$$\begin{aligned} i_{cap,4} &= i_{D,N} = \frac{0.3mA/V^2}{2}(2(3V - 20k\Omega \times i_{D,N} \\ &\quad -0.5V)(0.3V - 20k\Omega \times i_{D,N}) - (0.3V - 20k\Omega \times i_{D,N})^2) \end{aligned}$$

which after solving yields a current of only $0.24\mu A$ so it can be neglected.

The average current for discharging is thus about $22.8mA$ and

$$t_f \simeq 1pF\frac{2.4V}{22.8mA} = \boxed{105ps}$$

3. To estimate t_{PLH} we must consider $v_{IN} = 0V$ and two values for the output: $v_{OUT} = 0V$ and $V_{OUT} = 1.5V$.

   When $v_{OUT} = 0V$, $v_{SD,P} = 3V - 0.7V = 2.3V < v_{SG,P} + V_{tp} = 3V - 0.5V = 2.5V$, and Q_P operates in triode mode. Since there is enough voltage for Q_1 to be ON, the situation is similar to the one described for the above $i_{cap,1}$, and charging current is

$$i_{cap} = i_{e1} + i_{R_1} = \beta i_{DP} - (\beta - 1)\frac{0.7V}{R_1}$$

$$i_{DP} = \frac{1}{2}\frac{0.3mA/V^2}{4}\left(2\,(2.5V)\,2.3V - (2.3V)^2\right) = 0.233mA$$

$$i_{cap} = 100 \times 0.233mA - 99 \times \frac{0.7V}{20k\Omega} = 19.8mA$$

   When $v_{OUT} = 1.5V$, $v_{SD,P} = 3V - 0.7V - 1.5V = 0.8V < v_{SG,P} + V_{tp} = 3V - 0.5V = 2.5V$, and Q_P operates in triode mode. Since there is enough voltage for Q_1 to be ON, the charging current is

$$i_{cap} = 100 i_{DP} - 99\frac{0.7V}{R_1}$$

$$i_{DP} = \frac{1}{2}\frac{0.3mA/V^2}{4}\left(2\,(2.5V)\,0.8V - (0.8V)^2\right) = 0.126mA$$

$$i_{cap} = 100 \times 0.126mA - 99 \times \frac{0.7V}{20k\Omega} = 9.135mA$$

   The average current is $14.5mA$ and

$$t_{PLH} = 1pF\frac{1.5V}{14.5mA} = \boxed{104ps}$$