COE 360 Principles of VLSI Design

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Lecture#8

Threshold Voltage & Current Equations

1. Threshold voltage body bias effect
2. Channel length modulation
3. Drain punch-through
4. Impact ionization – Hot electrons
5. Spice DC parameters

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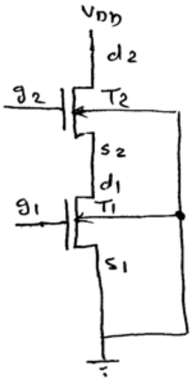
Threshold Voltage Body Effect:

So far, when analyzing MOS devices, we have assumed that the source and the substrate voltages are equal. However, when connecting MOS devices in series this assumption is no longer valid. Consider for example the structure of the NAND gate below.



In this case $V_{sb1} = 0$, however, $V_{sb2} \neq 0$ i.e. the voltage difference between the source and the substrate is not equal to 0. This effect changes the threshold voltage of T_2. The threshold voltage for T_2 becomes greater than T_1 i.e. $V_{t2} > V_{t1}$.

Thus, the threshold voltage is not constant with respect to the voltage difference between the substrate and the source of the MOS transistor.

This is known as the <u>body effect</u>.

To incorporate the effect of V_{sb}, the threshold voltage can be expressed as follows:

$$V_t = V_{fb} + 2\phi_b + \frac{\sqrt{2\varepsilon_{si}\, q\, N_A\,(2\phi_b + |V_{sb}|)}}{C_{ox}}$$

$$= V_{t0} + \gamma\left[\sqrt{(2\phi_b + |V_{sb}|)} - \sqrt{2\phi_b}\,\right]$$

where V_{sb} is the substrate bias, V_{t0} is the threshold voltage for $V_{sb} = 0$, and γ is the constant that describes the substrate bias effect, $\gamma = \dfrac{\sqrt{2\varepsilon_{si}\, q\, N_A}}{C_{ox}}$

* Typical values for $\underline{\underline{\gamma}}$ range from 0.4 to 1.2

As can be seen from the equation above, increase in $|V_{sb}|$ increases the threshold voltage of a MOS transistor.

<u>Example</u>

Assume $N_A = 3 \times 10^{16}\ cm^{-3}$, $t_{ox} = 200\ \text{Å}$, $\varepsilon_{ox} = 3.9 \times 8.85 \times 10^{-1}$ F/cm

$\varepsilon_{si} = 11.7 \times 8.85 \times 10^{-14}$ F/cm, and $q = 1.6 \times 10^{-19}\ C$

Find the threshold voltage V_t assuming

$V_{sb} = 2.5$ volts. $N_i = 1.5 \times 10^{10}$, $\dfrac{KT}{q} = 0.02586\ V$

$\text{Å} = 10^{-8}\ cm$

$$\gamma = \frac{0.2 \times 10^{-5}}{3.9 \times 8.85 \times 10^{-14}} \sqrt{2 \times 1.6 \times 10^{-19} \times 11.7 \times 8.85 \times 10^{-14} \times 3 \times 10^{16}}$$

$$= 0.57$$

$$\phi_b = 0.02586 \ln\left(\frac{3 \times 10^{16}}{1.5 \times 10^{10}}\right) = 0.375$$

$$V_{t2.5} = V_{to} + 0.57\left[\sqrt{0.75 + 2.5} - \sqrt{0.75}\right]$$

$$= V_{to} + 0.53$$

Thus, the thresholod increases by half a volt with the source at 2.5 volts for these process parameters.

Channel- length modulation

When an MOS device is in saturation, the effective channel length is described as

$$L_{eff} = L - L_{short}$$

where $L_{short} = \sqrt{2 \frac{\varepsilon_{si}}{q N_A} \left[V_{ds} - (V_{gs} - V_t)\right]}$

The reduction in channel length increases the $\left(\frac{W}{L}\right)$ ratio, therby increasing β as the drain voltage increases.

The drain current taking channel modulation into account can be represented as:

$$I_{ds} = \frac{\overset{=\frac{\mu\varepsilon}{t_{ox}} = \mu C_{ox}}{\textcircled{K}}}{2} \frac{W}{L} (V_{gs} - V_t)^2 (1 + \lambda V_{ds})$$

where K is the process gain factor $\frac{\mu\varepsilon}{t_{ox}}$, and λ is an empirical channel length modulation factor having a value in the range of $0.02\ V^{-1}$ to $0.005\ V^{-1}$.

Drain Punchthrough

When the drain is at a high enough voltage with respect to the source, the depletion region around the drain may extend to the source causing current to flow irrespective of the gate voltage (i.e. even if it is zero). This is known as a punchthrough condition.

Impact Ionization - Hot electrons

As the length of the gate of an MOS transistor is reduced, the electric field at the drain of a transistor in saturation increases (for a fixed drain voltage). For submicron gate lengths, the field can become so high that electrons will have high energy to become what is termed hot. These hot electrons impact the drain causing holes to be swept toward the negatively charged substrate and appear as a substrate current. This effect is known as impact ionization

Moreover, electrons can penetrate the gate oxide causing a gate current. This can lead to degradation of the MOS device parameters (threshold voltage, subthreshold current, —) which can lead to circuit failure.

Hot electrons effect will eventually push towards 3-volt and lower power supplies in CMOS design to improve device lifetime and reliability.

SPICE DC Parameters

Parameter	Description
VTO	V_t : threshold voltage
KP	$\frac{\mu \epsilon}{t_{ox}} = \mu C_{ox}$: Transconductance Coefficient
GAMMA	γ : Bulk threshold parameter
PHI	$2\Phi_b$: surface potential at strong inversion
LAMBDA	λ : Channel length modulation
TOX	t_{ox} : oxide thickness
NSUB	N_A : substrate doping density