MORE on MOSFET Capacitances

97.477 Lecture
January 15, 2003

Why we need today’s lecture.

This lecture completes the basic information on MOSFET capacitances.
An Example Application of the Lecture Information

You need to make a capacitor for a sample and hold circuit. For reasons of space constraints, you decide to use a MOSFET configured as a “MOSCAP”. How do you correctly size the MOSFET for the desired capacitance? What operating region do you use for the MOSFET, or does it really matter?

Intrinsic Capacitances
Intrinsic MOSFET Capacitances

Intrinsic MOSFET capacitances are significantly more complicated than extrinsic capacitances because they are a strong function of the voltages at the terminals and the field distributions within the device.

Although intrinsic MOSFET capacitances are distributed throughout the device, for the purposes of simpler modeling and simulation the distributed capacitances are normally represented by lumped terminal capacitances.

The terminal capacitances are derived by considering the change in charge associated with each terminal with respect to a change in voltage at another terminal, under the condition that the voltage at all other terminals is constant.

\[ C_{gd,i} = \left. \frac{\partial Q_G}{\partial V_D} \right|_{V_G, V_S, V_B} \]
\[ C_{gs,i} = \left. \frac{\partial Q_G}{\partial V_S} \right|_{V_G, V_D, V_B} \]
\[ C_{gb,i} = \left. \frac{\partial Q_G}{\partial V_B} \right|_{V_G, V_S, V_D} \]
\[ C_{bs,i} = \left. \frac{\partial Q_B}{\partial V_S} \right|_{V_G, V_D, V_B} \]
\[ C_{bd,i} = \left. \frac{\partial Q_B}{\partial V_D} \right|_{V_G, V_S, V_B} \]

These capacitances are evaluated in terms of the region of operation of the MOSFET, which is a function of the terminal voltages.
Intrinsic MOSFET Capacitances


Simplified expressions for the triode and saturation operating regions are given by:

<table>
<thead>
<tr>
<th>Operating Region</th>
<th>$C_{g_{s,i}}$</th>
<th>$C_{gd,i}$</th>
<th>$C_{gb,i}$</th>
<th>$C_{bs,i}$</th>
<th>$C_{bd,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triode</td>
<td>$\approx \frac{1}{2} C_{\alpha}$</td>
<td>$\approx \frac{1}{2} C_{\alpha}$</td>
<td>$\approx 0$</td>
<td>$k_0 C_{\alpha}$</td>
<td>$k_0 C_{\alpha}$</td>
</tr>
<tr>
<td>Saturation</td>
<td>$\approx \frac{2}{3} C_{\alpha}$</td>
<td>$\approx 0$</td>
<td>$k_1 C_{\alpha}$</td>
<td>$k_2 C_{\alpha}$</td>
<td>$\approx 0$</td>
</tr>
</tbody>
</table>

Notes: Triode region approximations are for $V_{DS} = 0$. $k_0$, $k_1$, and $k_2$ are bias dependent. See \(^1\).

1 Tsividis, Y. P., "Operation and Modeling of the MOS Transistor" 1987

MOSFET Total Terminal Capacitances

The total terminal capacitances are given by combining the extrinsic capacitances and intrinsic capacitances according to,

\[
C_{gs} = C_{gs,i} + C_{gs,e} = C_{gs,i} + C_{gsO} \\
C_{gd} = C_{gd,i} + C_{gd,e} = C_{gd,i} + C_{gdO} \\
C_{gb} = C_{gb,i} + C_{gb,e} = C_{gb,i} + C_{gbO} \\
C_{sb} = C_{bs,i} + C_{sb,e} = C_{bs,i} + C_{jsb} \\
C_{db} = C_{bd,i} + C_{db,e} = C_{bd,i} + C_{jdb}
\]
Total Gate-To-Channel Capacitance

The contribution of the total gate-to-channel capacitance, $C_{GC}$, to the gate-to-drain and gate-to-source capacitances is dependent upon the operating region of the MOSFET.

The total value of the gate-to-channel capacitance is determined by the per unit area capacitance $C_{ox}$ and the effective area over which the capacitance is taken.

Since the extrinsic overlap capacitances include some of the region under the gate, this region must be removed when calculating the gate to channel capacitance. The effective channel length, $L_{eff}$, is given by $L-2LD$ so that the gate to channel capacitance can be calculated by the formula $C_{GC}=C_{ox} \ W L_{eff}$.
The total value of the gate to channel capacitance is apportioned to both the drain and source terminals according to the operating region of the device.

When the device is in the triode region, the capacitance exists solely between the gate and the channel and extends from the drain to the source. Its value is therefore evenly split between the terminal capacitances $C_{gs}$ and $C_{gd}$.

When the device operates in the saturation region, the channel does not extend all the way from the source to the drain. No portion of $C_{gc}$ is added to the drain terminal capacitance under these circumstances. An appropriate amount of $C_{gc}$ to include in the source terminal capacitance is $2/3$ of the total.

Finally, the channel to bulk junction capacitance, $C_{bc}$, should be considered. This particular capacitance is calculated in the same manner as the gate to channel capacitance. Also similar to the gate to channel capacitance proportioning between the drain in the source when calculating the terminal capacitances, the channel to bulk junction capacitance is also proportioned between the source to bulk and drain to bulk terminal capacitances depending on the region of operation of the MOSFET.
If the MOSFET is in subthreshold ($V_{GS} < V_T$), then the primary capacitances are the overlap capacitances associated with the source/drain and gate:

$$C_{GS} = CGSO \times W$$
$$C_{GD} = CGDO \times W$$

The drain to bulk and source to bulk capacitances are given by the junction capacitance equations.

The gate to bulk capacitance is formed by the series combination of the gate to channel capacitance and the channel to bulk capacitance. See next slide.

$$C_{GC} = WL_{eff}C_{ox}$$

$$C_{dep} = WL_{eff}\sqrt{\frac{q\varepsilon_s N_{sub}}{4\Phi_F}}$$
Triode MOSFET Caps

If the MOSFET is in triode ($V_{GS} > V_T$ and $V_{DS} < V_{GS} - V_T$), and the drain to source voltage is low, then a change in the gate voltage will tend to draw equal amounts of charge from the source and from the drain. Under these conditions, the gate oxide capacitance is equally split between the source and drain, giving:

$$C_{GS} = C_{GS0} \times W + \frac{1}{2} W L_{eff} C_{ox}$$
$$C_{GD} = C_{GDO} \times W + \frac{1}{2} W L_{eff} C_{ox}$$

The drain to bulk and source to bulk capacitances are given by the junction capacitance equations.

The inversion layer tends to act as a conductive shield, and the gate to channel capacitance is no longer in series with the channel to bulk capacitance. Therefore $C_{GB} \approx 0$.

Saturation MOSFET Caps

If the MOSFET is in saturation ($V_{GS} > V_T$ and $V_{DS} > V_{GS} - V_T$), a change in the gate voltage will tend to draw unequal amounts of charge from the source and from the drain. Under these conditions, it can be shown that the gate oxide capacitance is unequally split between the source and drain, giving:

$$C_{GS} = C_{GS0} \times W + \frac{2}{3} W L_{eff} C_{ox}$$
$$C_{GD} = C_{GDO} \times W$$

The drain to bulk and source to bulk capacitances are given by the junction capacitance equations.

The inversion layer tends to act as a conductive shield, and the gate to channel capacitance is no longer in series with the channel to bulk capacitance. Therefore $C_{GB} \approx 0$. 
MOSFETs can be used as capacitors. A MOSFET capacitor (MOSCAP) can be made smaller than a poly-insulator-poly capacitor (PIPCAP) or metal-insulator-metal capacitor (MIMCAP). The MOSCAP is voltage dependent, and non-linear.
MOSCAP Example

When the MOSFET is in accumulation ($V_{GS} < 0$), holes are accumulated under the gate oxide. This results in a parallel plate capacitor with:

$$C_G \approx W L_{eff} C_{ox}$$
MOSCAP in Depletion

As $V_{GS}$ is increased, the number of holes under the gate decreases and a depletion region forms as the device enters weak inversion. The depletion capacitance is small, and when placed in series with the gate capacitance gives a low series capacitance to the bulk.

MOSCAP in INVERSION

As $V_{GS}$ is increased further, the inversion layer forms and the channel to bulk capacitance is “shielded”. Most of the MOSCAP capacitance is from $C_{GS}$. 
MOSCAP Summary

Prefer to operate in this region.

The Following Slides are Courtesy of Dan Olszewski
Voltage Controlled Oscillator

VG = 1 V  
Vth = 0.6V  
VSD = 0V

MOSCAPs

pmos MOSCAP capacitance with varied control voltage
NMOS CGS and CGD

VDS = 0.8V
Vth = 0.45V