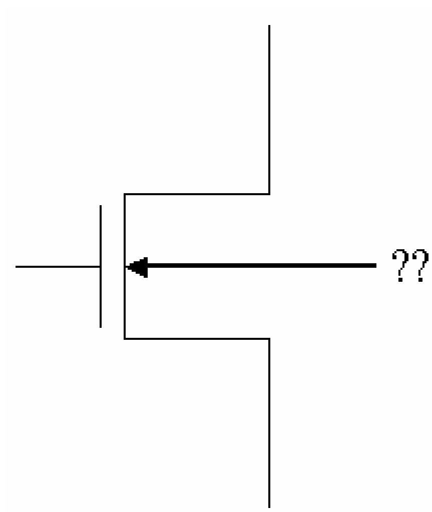
97.477 Analog Integrated Electronics
Assignment #3

The Importance of the Body Effect



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To simplify equations when doing hand derivations, the body effect is often ignored in many textbooks. However, this brings up an interesting question: can the body effect really be ignored when doing a design, or is it simply done in the academic environment to avoid making equations overly complicated when concepts are being taught?

To be able to safely ignore the body effect, which is defined as the variation of the threshold voltage of an FET due to a variation of the substrate or bulk voltage [1], the body terminal must be connected to the source terminal. This results in the pn junction between the substrate and the induced channel having a constant zero (cut-off) bias. In this case the substrate does not play any role in the circuit operation and its existence can be ignored altogether [2].

However, in many circuits it is not possible to connect the bulk and source terminals together. For example, in the configuration shown in Figure 1, the middle NMOS will experience the body effect if an n-well process is used, because all of the NMOS on this chip will have their bulk terminals connected to a common bulk, since the substrate is common to all of the NMOSs. In order to maintain the cut-off condition for all the substrate-to-channel junctions, the substrate is usually connected to the most negative power supply in an NMOS circuit (and the most positive power supply in a PMOS circuit) [2]. However, the body effect could be avoided by using a twin-tub process so that each transistor is in its own well, and could therefore have the source and bulk connected for each transistor (since there is no longer a common bulk connection). However this manufacturing process is much more expensive, and may not be appropriate for some applications.

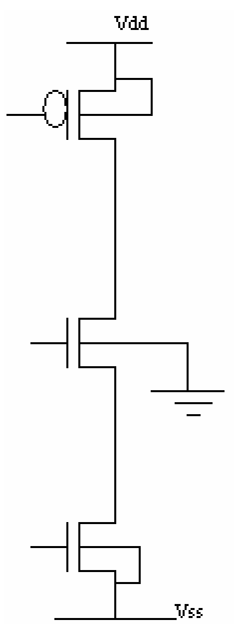

Figure 1: A MOSFET configuration using an n-well process. The middle NMOS will experience the body effect (assume Vss is actually ground) [3]

The resulting reverse-bias voltage between source and body (V_{SB} in an n-channel device) will have an effect on device operation. For example, for an NMOS transistor with a substrate that is negative relative to the source, the depletion region becomes wider. This has the effect of reducing the channel depth, and to therefore return the channel to its former state, V_{GS} must be increased [2].

The effect of V_{SB} on the channel is represented in terms of the threshold voltage, V_T, by the following relationship:

$$V_T = V_{T0} + \gamma\left[\sqrt{2\phi_f - V_{SB}} - \sqrt{2\phi_f}\right]$$

where is V_{T0} the threshold voltage for $V_{SB} = 0$; ϕ_f is the Fermi potential voltage, which is a physical parameter (typically $2\phi_f \approx 0.6V$).

γ is a fabrication - process paramter (i.e. the body - effect paramter) which is given by:

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_s}}{C_{ox}}$$

where is the N_A doping concentration of the p - type subtrate, ε_s and

is the permittivity of silicon (1.04×10^{-12} F / cm).

Typically $\gamma = 0.5V^{1/2}$

From the equation above it can be seen that an incremental change in V_{SB} will result in an incremental change in V_T, which then results in a change in I_{DS}, even though V_{GS} might have remained constant. Therefore it is as if the bulk contact acts as another gate for the MOSFET, since the bulk voltage controls I_{DS}. This can lead to degradation in the circuit performance as was observed during Lab 1 for this course.

During Lab 1 it was observed that in fact that body effect could not be ignored when doing a design because it can have a significant impact on the output voltage and current. It was due to this large potential impact that the body effect can have on a design, and yet the fact that it is generally ignored in textbooks, or only briefly mentioned in passing, that I decided to write about this topic. The need to consider the body effect was greatly stressed in this course, and made me realize that one has to be very careful when applying equations that have been derived using many simplifications.

From Lab 1, a stacked diode-connected MOSFET configuration was used both without the body effect and with the body effect present, as can be seen in Figure 2 and Figure 3.

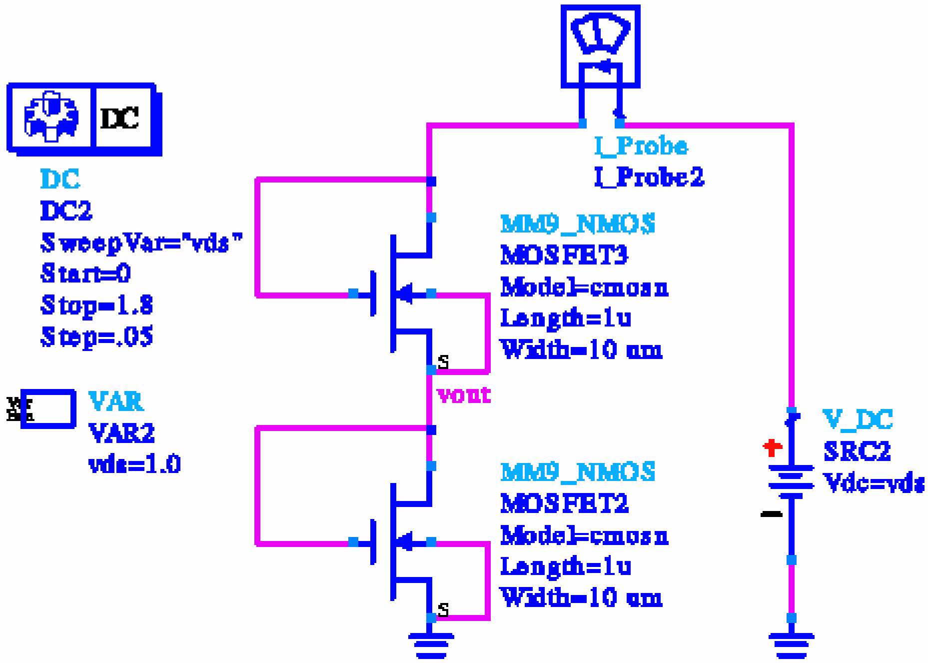

Figure 2: Stacked diode-connected MOSFETs, without the body effect [4]

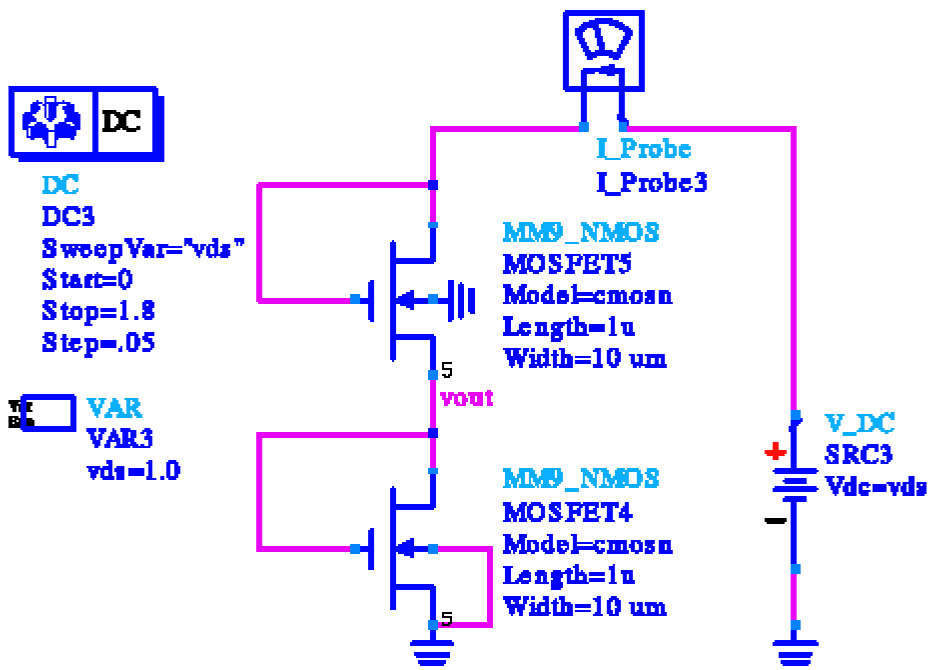

Figure 3: Stacked diode-connected MOSFETs, including V_{SB} (i.e. with the body effect) [4]

As part of the lab it was determined, analytically, that to obtain an output voltage of 1.0V, a width of 22.1 µm was needed for the top MOSFET. If the same configuration was used as in Figure 2, only this time with the bulk terminal not connected to the source but instead being connected to ground (see Figure 3), which would be the actual connection if this circuit was manufactured (using an n-well process), it was noticed that the output voltage dropped to approximately 802.6 mV. This is the expected result because the body effect results in an increase in the threshold voltage, V_T, as can be seen from the equations given above. Because the same current must flow through both MOSFETs when they are in this configuration, a decrease in V_T results in an increase in V_{GS} to compensate for the change. And V_{out} is related V_{GS} to as follows:

$$V_{out} = V_{DD} - V_{GS}$$

If V_{GS} increases (due to the increase in threshold voltage), and if V_{DD} is held constant, then V_{DD} must decrease.

To counteract this decrease in the output voltage, the top MOSFET's width may be increased (to increase the current, since a large width means lower resistance) to increase V_{out}, and therefore would compensate for the change in V_T due to the body effect.

To make V_{out} equal to the original 1.0V it was required that the top MOSFET's width be increased to 157 μm, which is a significant jump from the width of 22.1 μm that was required when the bulk terminal was connected directly to the source. This is a drastic increase in size, which could impact the layout of the circuit. It is therefore apparent that V_{SB} (and therefore the body effect) should not be ignored in design work because it can potentially lead to incorrect results, and lower V_{out} values than are expected (the actual impact that the body effect will have on the circuit will depend on the configuration of the circuit).

As was observed in our assignments for this course, trying to include the body effect into derivations of output resistance and gain values can greatly complicate the analysis. The added complexity seems to be the main reason that the assumption is made that the body effect can be neglected when circuits are analyzed. As well, in some situations (such as deriving the vo/vi equation for a basic differential pair) it has been shown, through simulations, that including the body effect does not significantly change the result and can therefore be safely ignored.

However, it must be remembered that the standard results that have been developed should only be used as a rough starting point for hand calculations and that these standard equations often include many simplifications and assumptions (either explicitly or implicitly) that may not actually model what would be observed in a manufactured circuit, or even in simulations. For this reason, it is very important to run simulations on a circuit to more accurately model such effects as the body effect and channel length modulation, which are routinely ignored in derivations.

This course has taught me the importance of understanding what simplifications have been made in deriving equations, and in determining how these simplifications could affect my designed circuits. Body effect was something that was briefly touched upon during the IC design course (97.469) but after completing this course I am better able to fully appreciate its effect on circuits. Also I am better at recognizing where the body effect could potentially occur.

References:

1. Van Zeghbroeck , B., “Chapter 7 Glossary.” http://ece-www.colorado.edu/~bart/book/book/chapter7/ch7_g.htm, 2002

2. Sedra, Adel S., Kenneth C. Smith, “Microelectronic Circuits.” Fourth Edition, Oxford University Press, 1998, p. 374

3. MacEachern, Leonard, 97.477 Quiz #1, 2003

4. MacEachern, Leonard, 97.477 Lab #1, 2003

As a side note:

It was asked in class to figure out how the units of the relationship of $R = 1/f_cC$ for switch capacitor work out, since $1/f_cC$ results in units of seconds/Farads. The answer is as follows:

$$R = \frac{1}{f_c C}$$

Units fc has units of Hz = / s, C has units of F

Therefore R has units: $\frac{s}{F}$, but the typical units for a resistor are $\Omega = \frac{V}{A}$

$1\ F = \frac{C}{V}$ and $C = sA$

Therefore: $\frac{s}{F} = s(\frac{V}{C}) = sV(\frac{1}{C}) = sV(\frac{1}{sA}) = \frac{V}{A} = \Omega$

So the units do work out to the expected unit of an ohm for a resistor â€¢ Integrated Soft Start â€¢ Integrated Loop Compensation â€¢ Real Time System Control on ILIM pin to Limit. Charge Current â€¢ AC Adapter Operating Range 9V-24V â€¢ 5ÂµA Off-State Battery Discharge Current â€¢ 20-pin 3.5 x 3.5 mm2 QFN Package. APPLICATIONS.Â (3) The junction-to-top characterization parameter, yJT, estimates the junction temperature of a device in a real system and is extracted from the simulation data for obtaining qJA, using a procedure described in JESD51-2a (sections 6 and 7). (4) The junction-to-board characterization parameter, yJB, estimates the junction temperature of a device in a real system and is extracted from the simulation data for obtaining qJA , using a procedure described in JESD51-2a (sections 6 and 7). 97.477 Analog Integrated Electronics Assignment #3. The Importance of the Body Effect. Course: 97.477A, Analog Integrated Electronics Student Name: CÃ©line Fletcher, 265474 Date Submitted: April 4, 2003 Professor: Len MacEachern. 2.Â This course has taught me the importance of understanding what simplifications have been made in deriving equations, and in determining how these simplifications could affect my designed circuits. Body effect was something that was briefly touched upon during the IC design course (97.469) but after completing this course I am better able to fully appreciate its effect on circuits. Also I am better at recognizing where the body effect could potentially occur. 6. Because of its importance and application to many different problems, an analysis of the depletion region of a reverse-biased pn junction is considered below. The properties of forward-biased pn junctions are treated in Section 1.3 when bipolar-transistor operation is described. Consider a pn junction under reverse bias as shown in Fig.Â carrier concentration in a pure sample of the semiconductor and n i 1.5 Ã— 10 10 cm â ̆'3 at 300 â€¢ K for silicon. In Fig. 1.1 the built-in potential is augmented by the applied reverse bias, V R , and the total voltage across the junction is (Ïˆ 0 + V R). If the depletion region penetrates a distance W 1 into the p-type region and W 2 into the n-type region, then we require (1.2) because the total charge per unit area on either.