A Simulation Circuit to Characterize Transistors

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Abstract—I present a simple simulation schematic to extract transistor parameters relevant for analog circuit design: transconductance g_m, transconductance per current g_m/I_d, and voltage gain g_m/g_o.

Keywords-SPICE, LTspice, MOSFET, process characterization, g_m/I_d design method
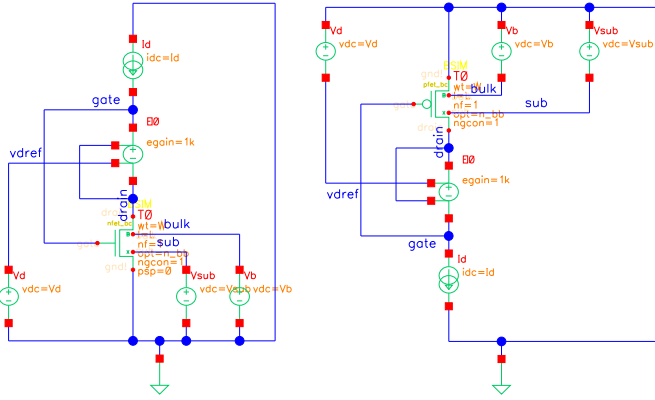
I. THE CIRCUIT

Fig. 1. Simulation schematics to characterize MOSFETs

The main design parameters for dimensioning MOSFETs are their drain current I_d, which controls transconductance, and the drain-to-source voltage V_{ds}, which controls output conductance g_o. However, the operating point of the transistor is controlled mostly by the gate-to-source voltage V_{gs}, which varies a lot between different wafers of the same IC design.

I solve this by regulating the gate voltage by a feedback loop that adjusts V_g to set the drain voltage V_d to a reference $V_{d,ref}$ by an ideal voltage controlled voltage source (VCVS) with voltage gain A. The schematics for the NMOS and PMOS simulation circuits are shown in Figure 1.

Kirchhoff's Current Law yields the small-signal equations

$$I_d = g_m V_g + g_o V_d \tag{1}$$
$$V_g = V_d + A\left(V_d - V_{d,ref}\right)$$

which lead to

$$V_g = \frac{I_d - g_o V_{d,ref} A/\left(1+A\right)}{g_m + g_o/\left(1+A\right)} \tag{2}$$

and

$$V_d = \frac{I_d + A\,g_m V_{d,ref}}{\left(1+A\right)g_m + g_o}. \tag{3}$$

In the ideal case of $A \to \infty$,

$$V_g = \frac{I_d - g_o V_{d,ref}}{g_m} \tag{4}$$

and

$$V_d = V_{d,ref}. \tag{5}$$

II. PARAMETER EXTRACTION

A. Transconductance

The transconductance g_m as function of drain current can be obtained by sweeping I_d for fixed V_d, as

$$1/\left(\frac{\partial V_g}{\partial I_d}\right) = g_m + g_o/\left(1+A\right) \overset{A\to\infty}{\approx} g_m. \tag{6}$$

B. g_m/I_d

The specific transconductance g_m/I_d is a useful design parameter for setting the bias point of a transistor [1]. g_m/I_d is maximal in subthreshold operation. It is obtained by sweeping I_d for fixed V_d and calculating

$$1/\left(\frac{\partial V_g}{\partial I_d} I_d\right) = \frac{g_m + g_o/\left(1+A\right)}{I_d} \overset{A\to\infty}{\approx} \frac{g_m}{I_d}. \tag{7}$$

C. g_m/g_o

While g_m or g_m/I_d is the most important design criterion for dimensioning a transistor, the next most important criterion is setting the output conductance g_o. With the circuits in Figure 1, the intrinsic voltage gain g_m/g_o can be extracted by sweeping $V_{d,ref}$ for constant I_d.

$$-\left(\frac{\partial V_d}{\partial V_{d,ref}}\right)/\left(\frac{\partial V_g}{\partial V_{d,ref}}\right) = \frac{\frac{A\,g_m}{(1+A)g_m+g_o}}{\frac{A\,g_o}{(1+A)g_m+g_o}} = \frac{g_m}{g_o}. \tag{8}$$

III. PARAMETER SWEEPS

A. Transconductance

Even when MOS transistor models are too complicated for hand calculations, the specific transconductance g_m/I_d indicates the operating region of the transistor [1].

In the weak inversion region, I_d is an exponential function of V_g,

$$I_d = I_{d0} \exp\left(\frac{q}{n\,k\,T}\left(V_g - V_t\right)\right) \tag{9}$$

with V_t the threshold voltage, q the electron charge, k the Boltzmann constant, T the absolute temperature, $n > 1$ a process dependent factor, and I_{d0} a proportionality constant depending on geometry, so

$$\frac{g_m}{I_d} = \frac{\frac{\partial I_d}{\partial V_g}}{I_d} = \frac{\frac{q}{n\,k\,T}I_{d0}\exp\left(\frac{q}{n\,k\,T}\left(V_g - V_t\right)\right)}{I_{d0}\exp\left(\frac{q}{n\,k\,T}\left(V_g - V_t\right)\right)} = \frac{q}{n\,k\,T}. \tag{10}$$

In the strong inversion region, I_d depends quadratically on V_g,

$$I_d = \frac{\kappa}{2}\left(V_g - V_t\right)^2 \tag{11}$$

with the threshold voltage V_t and a geometry and process dependent factor κ, so

$$\frac{g_m}{I_d} = \frac{\kappa\left(V_g - V_t\right)}{\frac{\kappa}{2}\left(V_g - V_t\right)^2} = \frac{2}{V_g - V_t} \tag{12}$$

where $V_g - V_t > 2\,\frac{n\,k\,T}{q}$ for the transistor to be above weak inversion.

With a logarithmic dc sweep of I_d at a given V_d, the transition between weak and strong inversion can be seen by g_m/I_d falling from its essentially constant value for weak inversion at the onset of strong inversion. g_m is obtained by taking the derivative with respect to the dc sweep variable I_d of both V_g and I_d. This is shown in LT Spice IV for two different processes (TSMC 250 nm and TSMC 180 nm) in Figures 2 and 3.
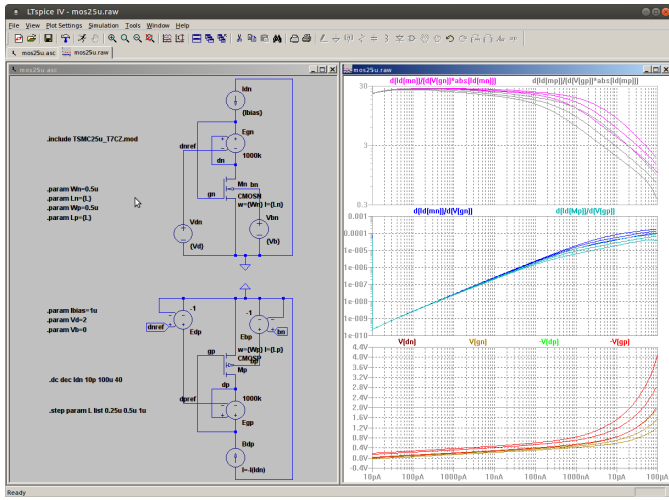

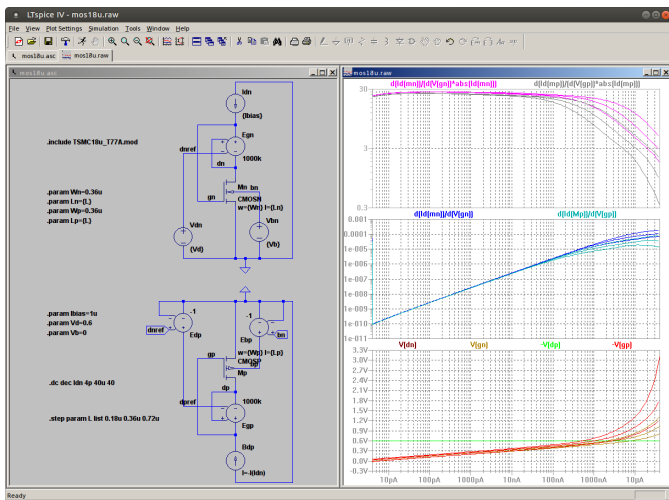Fig. 2. Transconductance characterization for 250 nm process

Fig. 3. Transconductance characterization for 180 nm process

For smaller W/L ratios, g_m/I_d starts dropping at lower I_d, and for the same W/L ratio, the g_m/I_d of PMOS transistors starts dropping at lower I_d than NMOS due to the lower mobility of holes vs. electrons.

For low-power, low noise circuits, the signal amplifying transistors should be dimensioned and biased in weak inversion near the onset of moderate inversion.
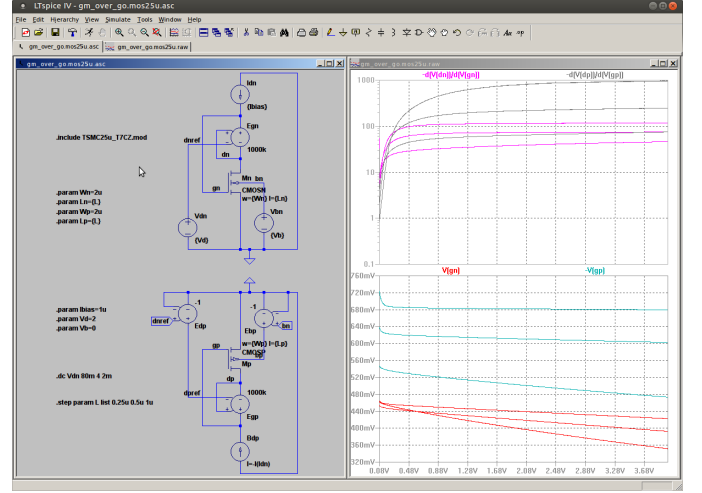
B. Voltage gain

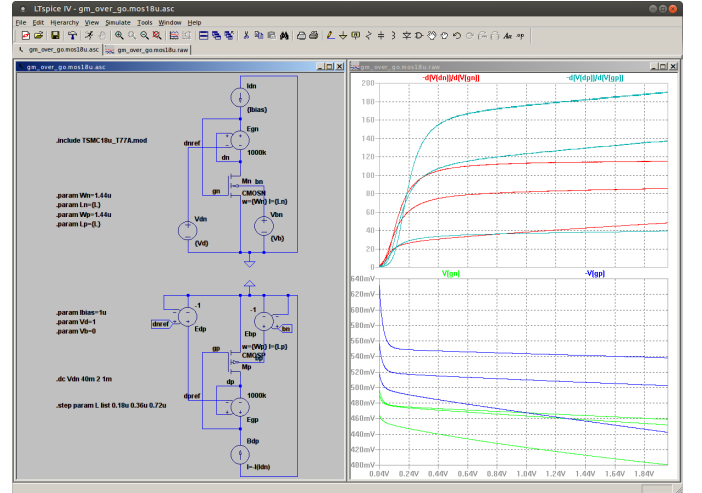Fig. 4. Voltage gain characterization for 250 nm process

Fig. 5. Voltage gain characterization for 180 nm process

For the dc voltage gain of a transistor stage, the transconductance to output conductance ratio g_m/g_o is the key figure of merit. g_o depends on transistor length and drain-to-source voltage V_{ds} in a way too complicated for hand calculations.

A linear sweep of V_d at constant I_d allows to optimize transistor length and minimum required V_{ds} to achieve the best possible voltage gain within design constraints for the process. g_m and g_o are obtained by taking the derivatives of V_g and V_d with respect to the dc sweep variable V_d, and calculating the ratio

$$\frac{g_m}{g_o} = -\frac{\mathrm{d}\left(V_d\right)}{\mathrm{d}\left(V_g\right)} \tag{13}$$

due to the implicit relation for constant I_d

$$g_o\,\mathrm{d}\left(V_d\right) + g_m\,\mathrm{d}\left(V_g\right) = 0\,. \tag{14}$$

Figures 4 and 5 show LT Spice IV linear V_d dc sweeps at different transistor lengths for two different processes (TSMC 250 nm and TSMC 180 nm).

Longer transistors have a higher g_m/g_o, PMOS can achieve higher g_m/g_o than NMOS, and the process with larger minimum feature size has higher maximal g_m/g_o.

IV. CONCLUSION

I present a single transistor simulation circuit, first published in the LT Spice Yahoo group in 2008 [2], with feedback control of the gate voltage V_g together with a method to dc sweep both I_d for constant V_d and V_d for constant I_d and a method to compute

$$g_m = \frac{\mathrm{d}\left(I_d\right)}{\mathrm{d}\left(V_g\right)} \quad \text{and} \quad \frac{g_m}{I_d} = \frac{\frac{\mathrm{d}(I_d)}{\mathrm{d}(V_g)}}{I_d} \tag{15}$$

from the I_d sweep, and

$$\frac{g_m}{g_o} = -\frac{\mathrm{d}\left(V_d\right)}{\mathrm{d}\left(V_g\right)} \tag{16}$$

from the V_d sweep.

This simulation circuit is suitable

- to get a quick overview of the properties of an unfamiliar IC process
- to set the dimension and bias points of transistors
- to design circuits using the g_m/I_d methodology. [1]

Coincidentally, the same feedback circuit, but without the parameter extraction methods, has been published in [3].

REFERENCES

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