Consistent parameter extraction using different MOSFET models


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On the ‘definitions’ of the threshold voltage

- Surface potential based $\phi_s = 2\phi_F + V_C$
- Qualitative: gate voltage at which *significant* drain current starts to flow
- Procedural based (details on next slide)

**Other approaches:**
- Splitting the threshold: define weak, moderate and strong inversion VTs
- Deconstructing the threshold: surface potential models don’t use VT as parameter!
The standard VT extraction methods

PROBLEM: missing link between extracted threshold and surface potential value!

MOSFET OPERATION: Drain current split into diffusion and drift components vs. gate voltage for a MOSFET operating in the linear region with $V_{DS} = \phi/2 = 13\text{mV}$. 

Sound modeling: To accurately extract $V_T$ it is essential that the MOSFET model includes the drift and diffusion transport mechanisms, both important near the threshold condition.

Extraction methods based solely on the strong (SI) or weak (WI) inversion models are inherently inaccurate since to determine the threshold voltage (which is found between the SI and WI regions) experimental data are extrapolated from only one of these two operating regions.
Current based definition of threshold 3


Take $I_{drift} = I_{diff}$ to define the threshold.

$$Q'_{ITH} = -(C'_{ox} + C'_b) \frac{kT}{q} = -nC'_{ox} \frac{kT}{q}$$

$C'_{ox}$ and $C'_b$ are the oxide and depletion capacitances per unit area.

The carrier charge density at threshold is the effective channel capacitance per unit area times the thermal voltage, or the thermal charge per unit area.
Charge-based all-region MOSFET model 1

Long-channel MOSFET

\[ I_D = I_F - I_R = I_S \left[ i_f - i_r \right] \]

\( I_F \): forward current

\( I_R \): reverse current

Specific or normalization current \( I_S \)

\[ I_S = \mu C'_ox n \frac{\phi_t^2 W}{2L} \]

\[ \phi_t = \frac{kT}{q} \quad n = 1 + \frac{C'_b}{C'_{ox}} \]

\( C'_{ox} \quad C'_b \) oxide and depletion capacitances per unit area
Charge-based all-region MOSFET model 2

\[ I_D = I_F - I_R = I_S \left[ i_f - i_r \right] \]

\[ q'_i = \frac{Q'_i}{-nC_{ox}'\phi'} \]  
Normalized inversion charge density

\[ i'_{f(r)} = q'_{IS(D)}^2 + 2q'_{IS(D)} \Rightarrow q'_{IS(D)} = \sqrt{1+i'_{f(r)}} - 1 \]

Drift  Diffusion

Threshold condition at the source:

\[ q'_{IS} = 1 \rightarrow i_f = 3 \]
Our approach $I_{\text{TH}} = 3I_S = 1.5(W/L)\mu C'_{\text{ox}} n\varphi_t^2$

EKV $I_{\text{TH}} = 0.608I_{\text{SPEC}} = 1.216(W/L)\mu C'_{\text{ox}} n\varphi_t^2$

\[ I_{\text{TH-sat}} = I_D|V_P = V_S = \left(q_s^2|V_P = V_S + q_s|V_P = V_S \right)I_{\text{SPEC}} \]
\[ = 0.608I_{\text{SPEC}}, \quad \text{where } q_s|V_P = V_S = F^{-1}(0). \quad (6) \]

Then, threshold voltage $V_{\text{TH}}(V_T)$ in saturation is determined as the value of $V_{GS}(V_G)$ for which the drain current is equal to approximately $0.6I_{\text{SPEC}}$. 

$k$ is Boltzmann constant, $T$ is temperature in Kelvin, $q$ is the electron charge, $n$ is the slope factor, $\mu$ is the mobility, $C_{\text{ox}}$ is the oxide capacitance per unit area, $W$ and $L$ are the effective width and length of the MOS transistor.
\[ g_m = \frac{1}{I_D} \frac{dI_D}{dV_G} = \frac{g_{ms} - g_{md}}{nI_D} = \frac{2}{n\phi_i \left( \sqrt{1+i_f} + \sqrt{1+i_r} \right)} \]

Thus, at threshold \( i_f = 3 \)

\( g_m/I_D \) is \( \frac{1}{2} \) of its maximum value

\( n = n(V_G) \equiv \text{constant} \)

For \( V_{DS} = (1/2)kT/q \), \( g_m/I_D \)

\( = 0.531 (g_m/I_D)_{\text{max}} \) and \( I_D = 0.88*I_S \)
$g_m/I_D$ $V_T$-extraction for a 3.5/0.5 nMOSFET simulated by BSIM6

$V_{T0} = 227$ mV
$n=1.315$

Gm/ID from BSIM6

WI model

BSIM6
CMOS inverter at $V_{DD} = 150$ mV
CMOS inverter at VDD = 100 mV
CMOS inverter at VDD = 50 mV
Ring oscillator
Transient simulation of the ring oscillator
Transient time analysis: BSIM6 vs. WI model
Conclusions

- The fundamental problem in switching between transistors models is to consistently determine the parameters of the different models.
- The \( g_m/ID \) procedure in the linear region allows determining accurately the most critical MOS parameters: the threshold voltage, the slope factor, and the specific current.
- Examples comparing simulations carried out with BSIM6 model and a simple weak inversion MOSFET model show good agreement for very low voltage circuits.
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