# Design and Simulation of RF Integrated Circuits with Open-Source CAD Tools and Process Design Kits

SLIDES >>>>>>>>>

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# Tutorial Outline

- **Part 1:**

**Advanced Compact MOSFET Model 2 - ACM2 model**

- **Part 2:**

**Implementing the ACM2 model**

- **Part 3:**

**ACM2 - Parameter extraction**

- **Part 4:**

**Design Methodology-Application to Low Noise Amplifier**

# Part 1
# Advanced Compact MOSFET Model: ACM2

"Scan me"

Carlos Galup-Montoro

https://github.com/ACMmodel/MOSFET_model

# Outline

- Introduction: ACM timeline
- ACM2 model
- Long-channel: $I_D$ and $g_m/I_D$ models

# ACM timeline

- 1993 $\phi s$-based model (SBMICRO, Campinas, Br)
- 1995 Long-channel charge-based model (SSE, Nov.)
- 1998 Most referenced ACM paper (JSSC, Oct.)
- 2000 ACM model in SMASH simulator ( CICC, Orlando)

- 2018  Short course on ACM for ST organized by Prof. Silvain at Grenoble
- 2021 4-parameter single-piece model (NorCAS, Oslo)
- 2023 ACM2 in VERILOG-AMS ( NEWCAS, Edinburgh)

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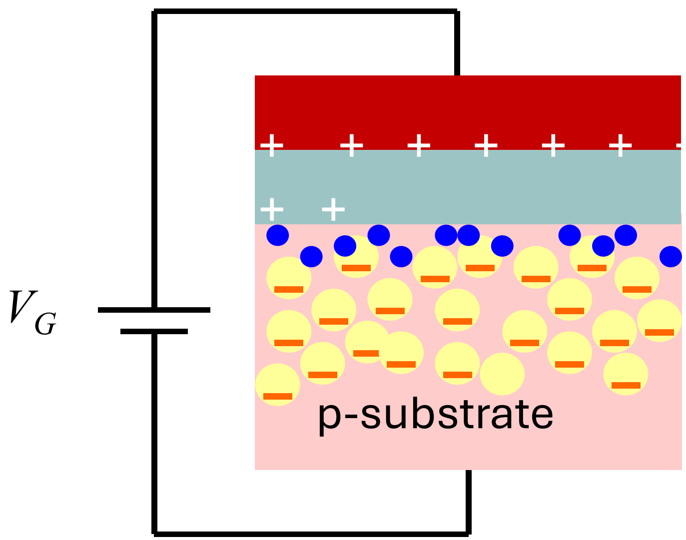
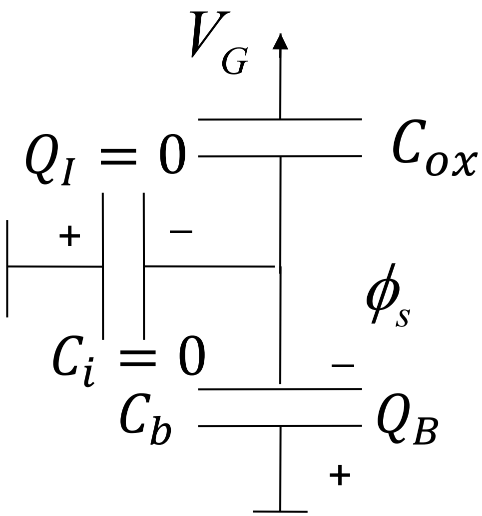
# The capacitive model of the MOSFET




$\phi_s$ **surface potential**

$$\frac{\Delta\phi_s}{\Delta V_G} = \frac{C_{ox}}{C_{ox} + C_b} = \frac{1}{n}$$

$C_{ox}$ **oxide capacitance per unit area**

$C_b$ **depletion capacitance per unit area**

$$\phi_s = 2\phi_F + \frac{V_G - V_{T0}}{n} = 2\phi_F + V_P$$

$Q_I$ **carrier charge density**

$V_{T0}$ **threshold voltage**

# ACM2 current law

From 3 approximations: normalized current vs. normalized charge densities at source and drain

$$i_D = \frac{(q_S + q_D + 2)}{1 + \zeta(q_S - q_D)}(q_S - q_D)$$

$i_D = I_D / I_S$

$$I_S = \frac{W}{L}\mu_s n C_{ox}\frac{\phi_t^2}{2}$$

normalization (specific) current

$q_{S(D)} = Q_{S(D)}/(-nC_{ox}\phi_t)$

$-nC_{ox}\phi_t$ thermal charge

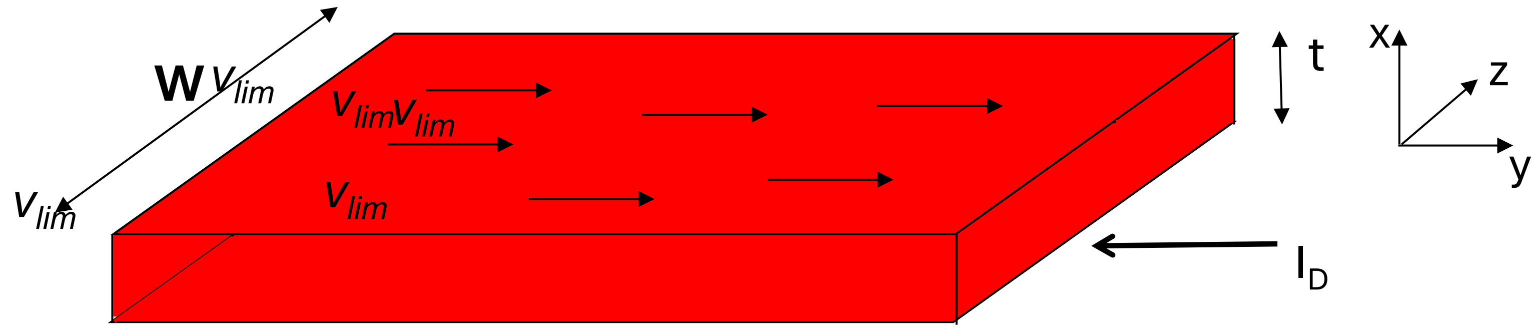
***SI :*** $q_{S(D)} >> 1$ *WI :* $q_{S(D)} << 1$

Short-channel parameter $\zeta$ :

$$\zeta = \frac{(\mu_s \phi_t / L)}{v_{lim}}$$

ratio of diffusion-related velocity to saturation velocity

# Physics-based saturation




Saturation current due to saturation velocity of the carriers

$$I_{Dsat} = -W Q_{Dsat}\, v_{lim}$$

$Q_{Dsat}$ is the saturation inversion charge per unit area

or, using normalized variables

$$i_{Dsat} = \frac{2}{\zeta} q_{dsat}$$

"Carrier velocity approaches $v_{sat}$, but never reaches $v_{sat}$"
Y.Taur TED March 2019

# Physics-based saturation: design model

$$i_{Dsat} = \frac{2}{\zeta} q_{dsat} \qquad\qquad i_{Dsat} = \frac{(q_S + q_{Dsat} + 2)}{1 + \zeta(q_S - q_{Dsat})}(q_S - q_{Dsat})$$

$$q_{Dsat} = q_s + 1 + \frac{1}{\zeta} - \sqrt{\left(1 + \frac{1}{\zeta}\right)^2 + \frac{2q_S}{\zeta}}$$

**or equivalently**

$$q_s = \sqrt{1 + \frac{2}{\zeta} q_{dsat}} - 1 + q_{dsat}$$

# The Unified Charge Control Model (UCCM)

$$\frac{V_P - V_C}{\phi_t} = q_I - 1 + \ln q_I$$

$$V_S \leq V_C \leq V_D$$

$$q_S \leq q_I \leq q_D$$

$$\Rightarrow \quad \frac{V_{DS}}{\phi_t} = q_S - q_D + \ln\frac{q_S}{q_D}$$

The "Regional" Weak (WI) and Strong Inversion (SI) Approximations

**WI**

$$q_I \ll 1 \;\rightarrow V_P - V_C \ll -\phi_t$$

$$q_I \cong e^{\frac{V_P - V_C + \phi_t}{\phi_t}}$$

Error <10% for $q_I < 0.22$

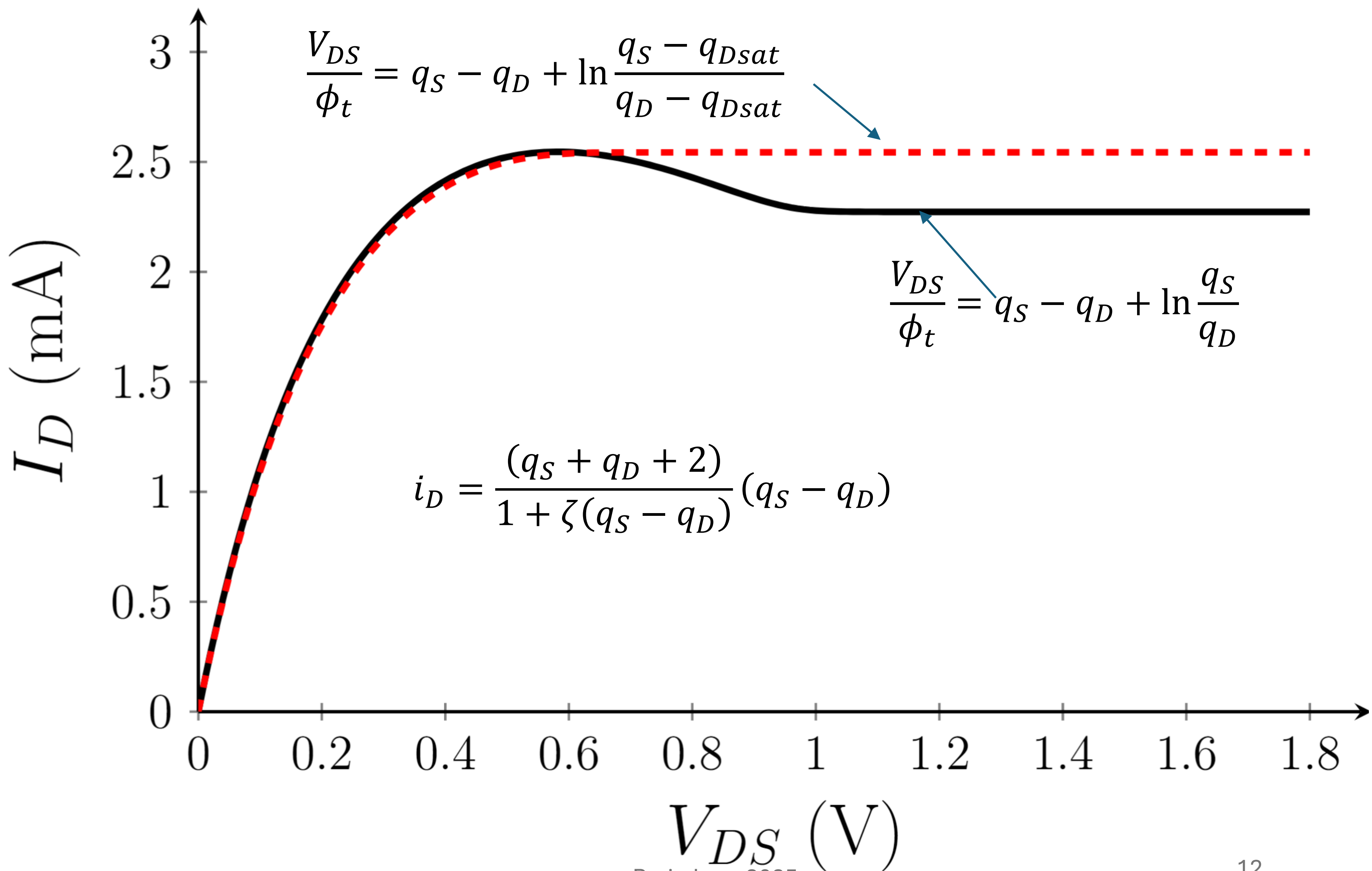
**SI**

$$q_I \gg 1 \;\rightarrow V_P - V_C \gg \phi_t$$

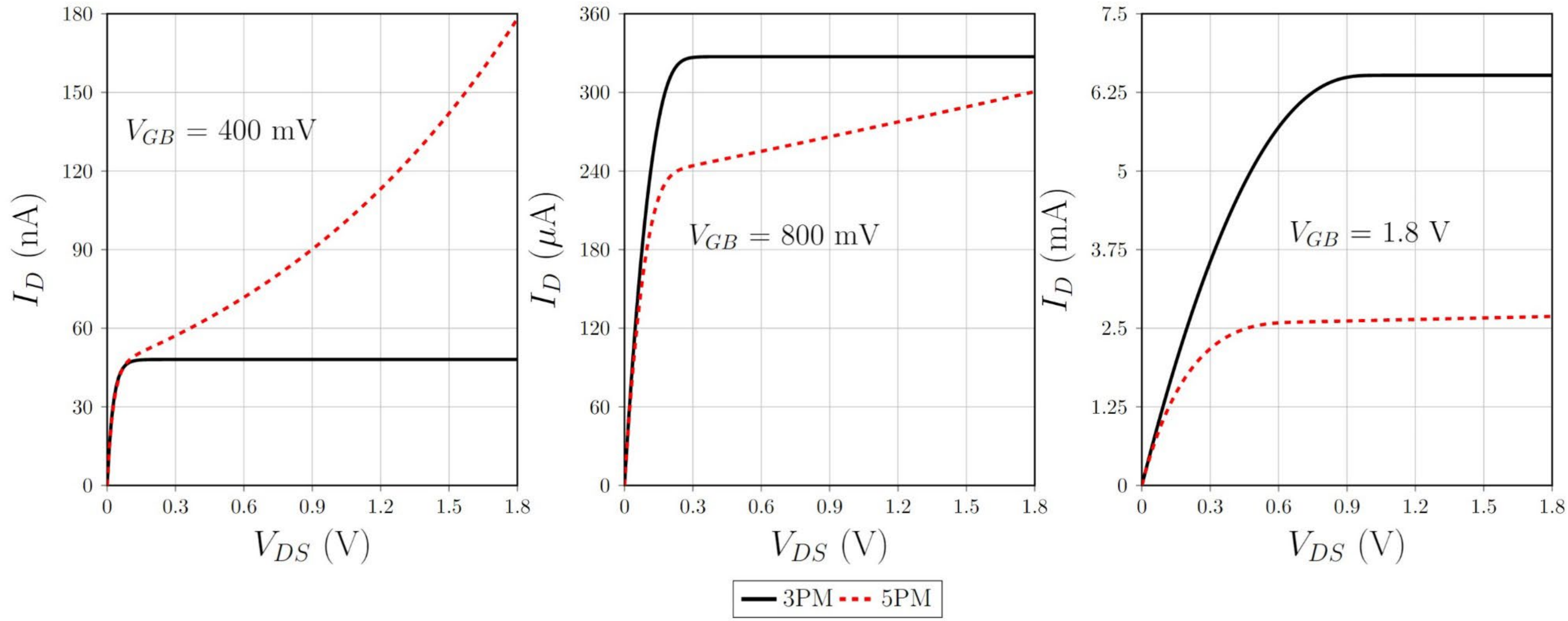
$$q_I \cong \frac{V_P - V_C + \phi_t}{\phi_t}$$

Error <10% for $q_I > 20$

# UCCM including the effect of velocity saturation



# Output curves including DIBL and $v_{sat}$




$$DIBL\ model: V_T = V_{T0} - \sigma(V_S + V_D)$$

| Transistor | $W/L$ $(\mu m/\mu m)$ | $V_{T0}$ $(mV)$ | $I_S$ $(\mu A)$ | n | $\sigma$ | $\zeta$ |
|---|---|---|---|---|---|---|
| NMOS2V | $\mathbf{5/0.18}$ | 528 | 5.52 | 1.37 | 0.025 | 0.056 |

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- **Introduction: ACM timeline**
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- **Long-channel: $I_D$ and $g_m/I_D$ models**

# Long-channel charge-based model

$For\ short\ channel\ MOS$ $$I_D = I_S \frac{(q_S + q_D + 2)}{1 + \zeta(q_S - q_D)}(q_S - q_D)$$

$$\frac{V_P - V_S}{\phi_t} = q_S - 1 + \ln q_S \qquad \frac{V_{DS}}{\phi_t} = q_S - q_D + \ln \frac{q_S - q_{Dsat}}{q_D - q_{Dsat}}$$

$For\ long\ channel\ MOS$ $\zeta$=0 → $q_{Dsat}$=0

$$I_D = I_S(q_S + q_D + 2)(q_S - q_D) = I_S[(q_S^2 + 2q_S) - (q_D^2 + 2q_D)]$$

$$\frac{V_P - V_{S(D)}}{\phi_t} = q_{S(D)} - 1 + \ln q_{S(D)}$$

Obs: $\frac{dq_{S(D)}}{dV_G} = -\frac{1}{n}\frac{dq_{S(D)}}{dV_{S(D)}}$ $\qquad \frac{dq_D}{dV_D} = -\frac{1}{\phi_t}\frac{q_D}{q_D + 1}$ $\qquad \frac{dI_D}{dq_D} = -2I_S(q_D + 1)$

# Small-signal transconductances

$$g_{md} = \frac{dI_D}{dV_D} = \frac{dI_D}{dq_D}\frac{dq_D}{dV_D} = 2I_S(q_D+1)\frac{1}{\phi_t}\frac{q_D}{q_D+1} = \frac{2I_S}{\phi_t}q_D$$

Symmetry

**Amazingly simple (see Appendix)**

$$g_{ms} = \frac{2I_S}{\phi_t}q_S$$

$$g_m = \frac{dI_D}{dV_G} = \frac{dI_D}{dq_S}\frac{dq_S}{dV_G} + \frac{dI_D}{dq_D}\frac{dq_D}{dV_G}$$

$$\frac{dq_{S(D)}}{dV_G} = -\frac{1}{n}\frac{dq_{S(D)}}{dV_{S(D)}}$$

$$\boxed{g_m = \frac{g_{ms}-g_{md}}{n}}$$

$$g_m = \frac{g_{ms}}{n} \longrightarrow \text{in saturation}$$

# Unified Current Control Model (UICM)-I

$$\boxed{I_D = I_S[(q_S^2 + 2q_S) - (q_D^2 + 2q_D)]}$$ (A)

(A) can also be written as

$$\boxed{I_D = I_F - I_R = I_S\left[i_f - i_r\right]}$$ (B)

$\boxed{I_F, I_R}$ : forward and reverse currents

$\boxed{i_{f(r)} = q_{S(D)}^2 + 2q_{S(D)}}$ : forward (reverse) inversion coefficients

$$\downarrow$$

$$q_{S(D)} = \sqrt{1 + i_{f(r)}} - 1$$

# Unified Current Control Model (UICM)-II

$$\frac{V_P - V_{S(D)}}{\phi_t} = q_{S(D)} - 1 + \ln q_{S(D)}$$

$$\boxed{q_{S(D)} = \sqrt{1 + i_{f(r)}} - 1}$$

## Normalized UICM

$$\boxed{\frac{V_P - V_{S(D)}}{\phi_t} = \sqrt{1 + i_{f(r)}} - 2 + \ln\left(\sqrt{1 + i_{f(r)}} - 1\right)}$$

$$\frac{V_{DS}}{\phi_t} = q_S - q_D + \ln\frac{q_S}{q_D} = \sqrt{1 + i_f} - \sqrt{1 + i_r} + \ln\left(\frac{\sqrt{1 + i_f} - 1}{\sqrt{1 + i_r} - 1}\right)$$

# $g_m/I_D$

$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1+i_{f(r)}}-1\right) = \frac{W}{L}\mu C_{ox} n\phi_t\left(\sqrt{1+i_{f(r)}}-1\right)$$

$$g_m = \frac{g_{ms}-g_{md}}{n}$$

$$\boxed{\frac{g_m}{I_D} = \frac{2}{n\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}}$$

For $V_{DS}/\phi_t$<<1 we have $i_f \cong i_r$

$$\boxed{\frac{g_m}{I_D} \cong \frac{1}{n\phi_t\sqrt{1+i_f}}}$$

In saturation $i_f >> i_r$

$$\boxed{\frac{g_m}{I_D} \cong \frac{2}{n\phi_t\left(\sqrt{1+i_f}+1\right)}}$$

# REFERENCES


- A. I. A. Cunha, M. C. Schneider and C. Galup-Montoro,"Derivation of the Unified Charge Control Model and Parameter Extraction Procedure", Solid-State Electronics, March 1999.
- O. C. Gouveia Filho, A. I. A. Cunha, M. C. Schneider and C. Galup-Montoro, "Advanced compact model for short-channel MOS transistors", IEEE Custom Integrated Circuits Conference, Orlando, FL, USA, May 2000.
- C. Galup-Montoro and M. C. Schneider, *MOSFET Modeling for Circuit Analysis and Design*, World Scientific, 2007.
- C. M. Adornes, D. G. Alves Neto, M. C. Schneider and C. Galup-Montoro, " Bridging the Gap between Design and Simulation of Low-Voltage CMOS Circuits ," Journal of Low Power Electronics and Applications, June 2022.
- D. G. Alves Neto *et al,* “Design-oriented single-piece 5-DC parameter MOSFET model,” *IEEE Access*, 2024.

# Appendix: the exact model of the long-channel MOSFET[1]

$$I_D = -\frac{W}{L}\int_{V_S}^{V_D} \mu Q_I\,(V_C)d\,V_C$$

Consequently, the **exact** expressions for $g_{ms}$ and $g_{md}$ are

$$g_{md} = \frac{dI_D}{dV_D} = -\frac{W}{L}\mu Q_D = \frac{2I_S}{\phi_t} q_D$$

$$g_{ms} = -\frac{dI_D}{dV_S} = -\frac{W}{L}\mu Q_S = \frac{2I_S}{\phi_t} q_S$$

[1] H. C. Pao and C. T. Sah, 'Effects of diffusion current on characteristics of metal-oxide (insulator)-semiconductor transistors" Solid-State Electronics, Oct 1966