Theory, development, and applications of the Advanced Compact MOSFET (ACM) model

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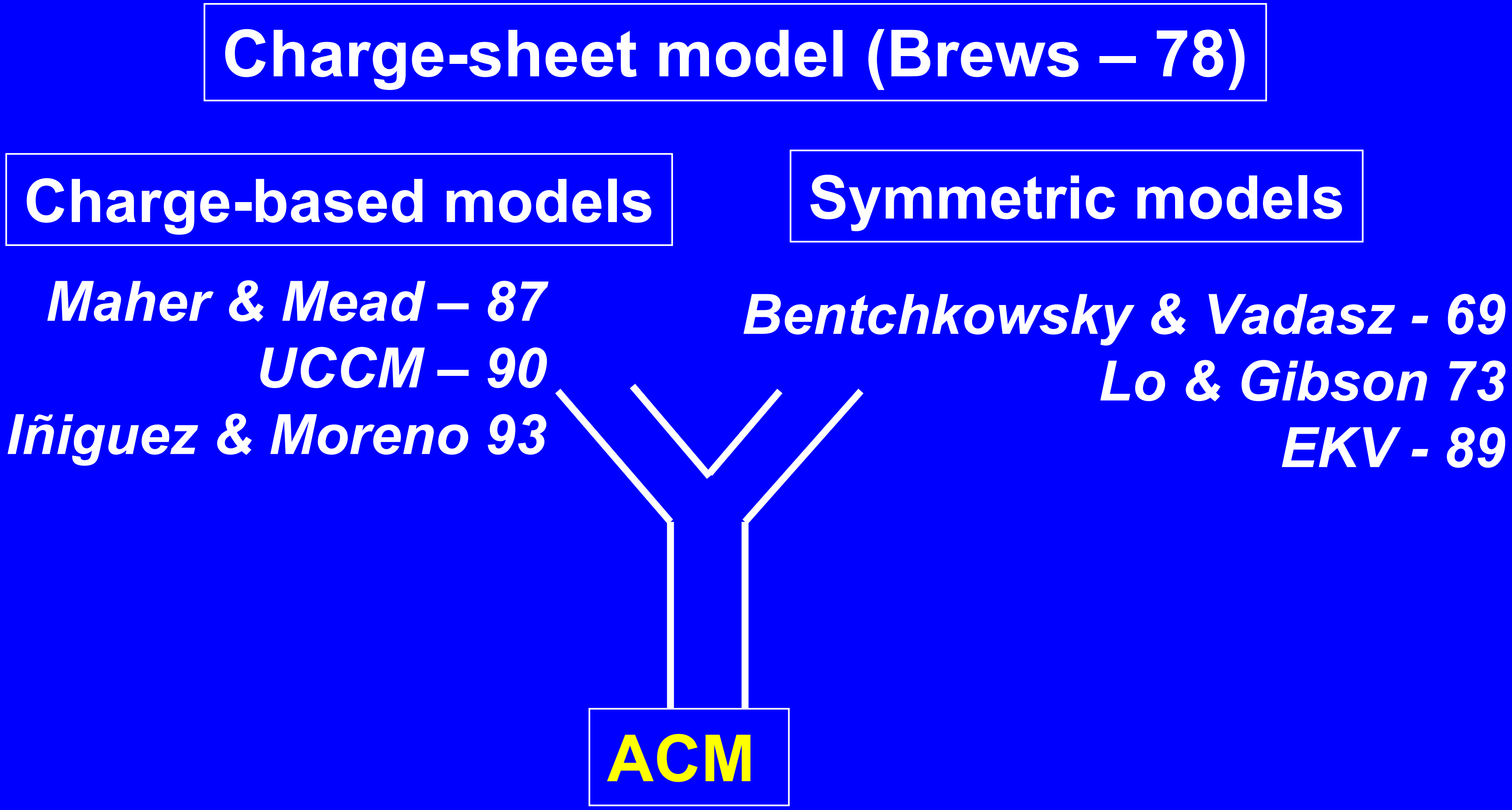
Introduction

Genealogy of the ACM Model



Charge-sheet model (Brews – 78)

Charge-based models

Maher & Mead – 87
UCCM – 90
Iñiguez & Moreno 93

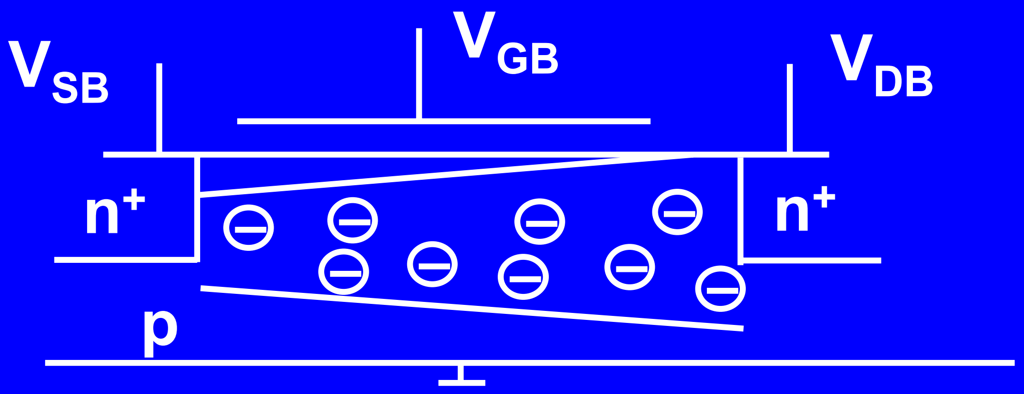
Symmetric models

Bentchkowsky & Vadasz - 69
Lo & Gibson 73
EKV - 89

ACM

Fundamentals

Depletion-Capacitance Approximation



C'$_b$, calculated assuming the inversion charge density to be negligible, is constant along the channel

$$Q'_I = -C'_{ox}\left(V_{GB}-V_{FB}-\phi_S-\gamma\sqrt{\phi_S}\right) \cong \left(1+\frac{\gamma}{2\sqrt{\phi_{sa}}}\right)C'_{ox}\left(\phi_s-\phi_{sa}\right) = \left(C'_{ox}+C'_b\right)\left(\phi_s-\phi_{sa}\right)$$

Basic relationships:

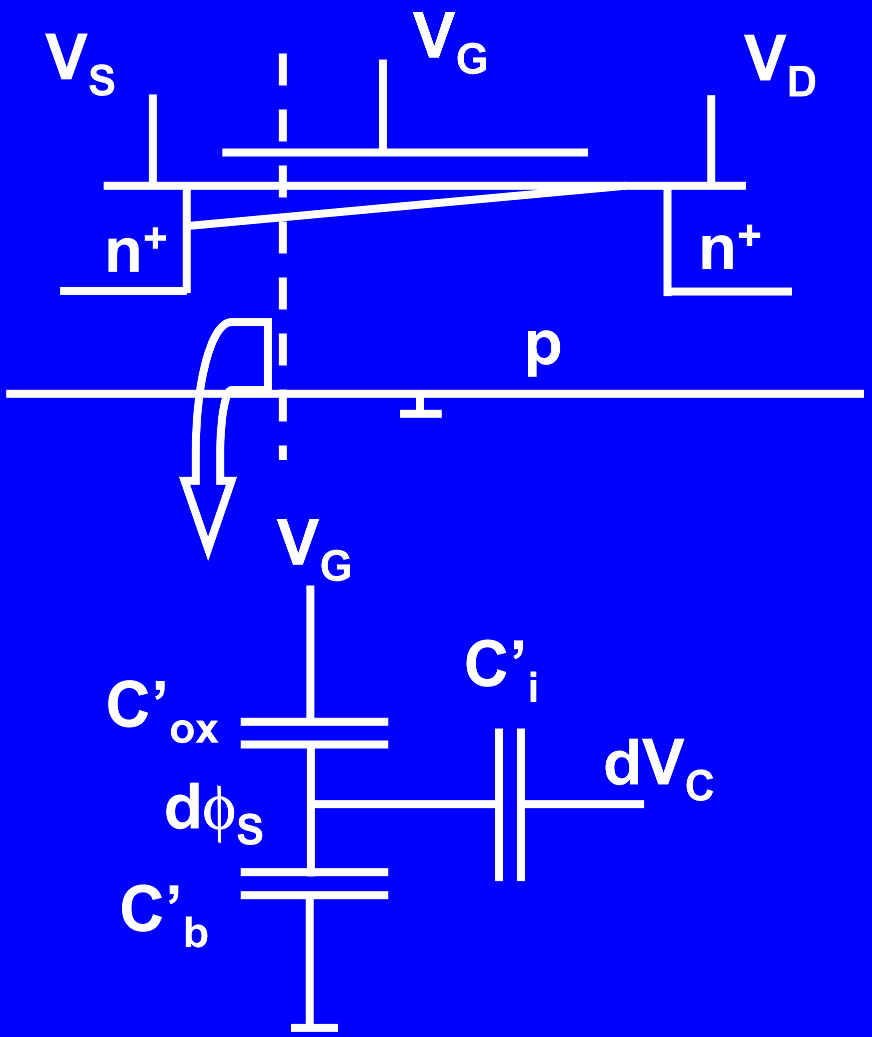
The inversion and depletion charge densities are incrementally linear functions of the surface potential

$$dQ'_I = \left(C'_{ox} + C'_b\right) d\phi_s = nC'_{ox} d\phi_s$$

$$dQ'_B = -C'_b d\phi_s = -\left(n-1\right) C'_{ox} d\phi_s$$

$$C'_b = C'_{ox} \frac{\gamma}{2\sqrt{\phi_{sa}}}$$

The Unified Charge Control Model



$$\left.\frac{dQ'_I}{dV_C}\right|_{V_G} = \frac{\left(C'_{ox}+C'_b\right)C'_i}{C'_{ox}+C'_b+C'_i}$$

Basic approximations:

$C'_{ox} + C'_b = nC'_{ox}$

$C'_i = -Q'_I/\phi_t$

$$\Downarrow$$

$$dQ'_I\left(\frac{1}{nC'_{ox}} - \frac{\phi_t}{Q'_I}\right) = dV_C$$

The Unified Charge Control Model

Integrating $dQ'_I\left(\frac{1}{nC'_{ox}}-\frac{\phi_t}{Q'_I}\right)=dV_C$ between V_C and V_P:

$$\boxed{\frac{Q'_{IP}-Q'_I}{nC'_{ox}}+\phi_t \ln\left(\frac{Q'_I}{Q'_{IP}}\right)=V_P-V_C}$$ **UCCM**

$Q'_{IP}=-nC'_{ox}\phi_t$: inversion charge at "pinch-off"

In strong inversion: $-Q'_I \cong nC'_{ox}\left(V_P-V_C\right)$

In weak inversion: $\phi_t \ln\left(\frac{Q'_I}{Q'_{IP}}\right)\cong V_P-V_C$

Drain Current

$$I_D = \mu W \left(\underset{\substack{\downarrow \\ \text{drift}}}{-Q'_I \frac{d\phi_s}{dx}} + \underset{\substack{\downarrow \\ \text{diffusion}}}{\phi_t \frac{dQ'_I}{dx}} \right)$$

Using the approximation

$$dQ'_I = nC'_{ox} d\phi_s$$

and integrating from source to drain:

$$I_D = -\frac{\mu}{nC'_{ox}} \frac{W}{L} \int_{Q'_{IS}}^{Q'_{ID}} \left(Q'_I - nC'_{ox}\phi_t \right) dQ'_I$$

$$I_D = I_F - I_R = I(V_G, V_S) - I(V_G, V_D)$$

$$I_{F(R)} = \mu n C'_{ox} \frac{W}{L} \frac{\phi_t^2}{2} \left[\left(\frac{Q'_{IS(D)}}{nC'_{ox}\phi_t} \right)^2 - 2\frac{Q'_{IS(D)}}{nC'_{ox}\phi_t} \right]$$

Drain Current

$$\frac{Q'_{IS(D)}}{-nC'_{ox}\phi_t} = \sqrt{1+i_{f(r)}} - 1$$

$$i_{f(r)} = \frac{I_{F(R)}}{I_S}$$

Forward (reverse) normalized current

$$I_S = \frac{1}{2} n\mu C'_{ox}\phi_t^2 \frac{W}{L}$$

Normalization (specific) current

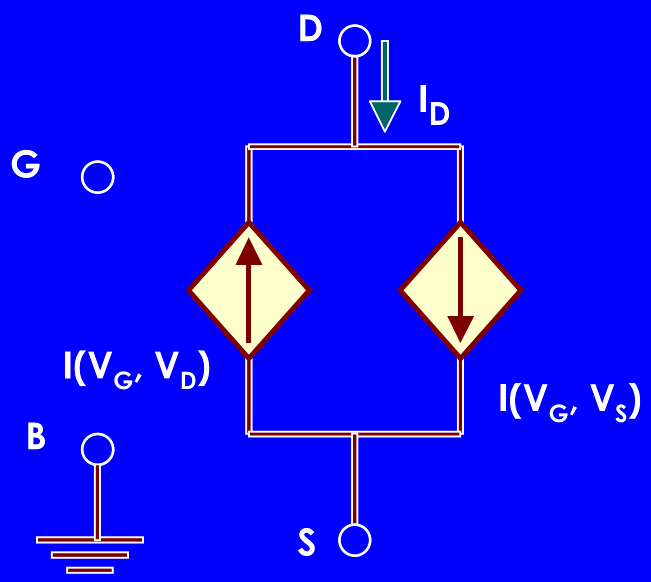
UICM →

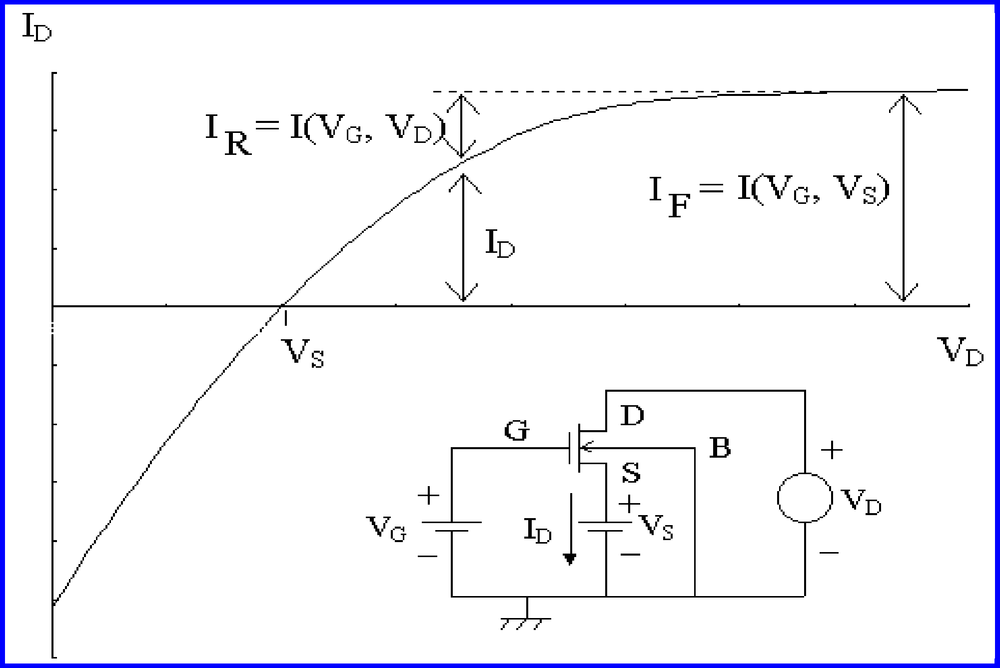
$$\boxed{\sqrt{1+i_{f(r)}} - 2 + \ln\left(\sqrt{1+i_{f(r)}} - 1\right) = \frac{V_P - V_{S(D)}}{\phi_t}}$$

Drain Current:

Forward and Reverse Currents

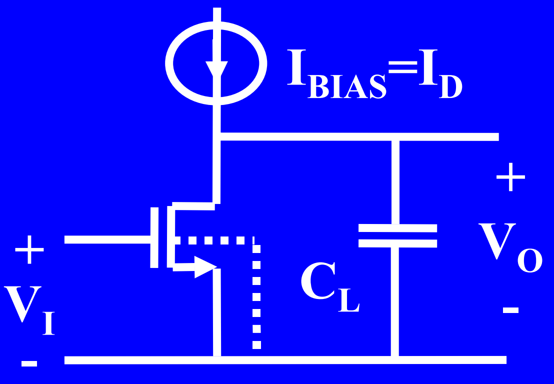
$$I_D = I_F - I_R = I(V_G, V_S) - I(V_G, V_D)$$





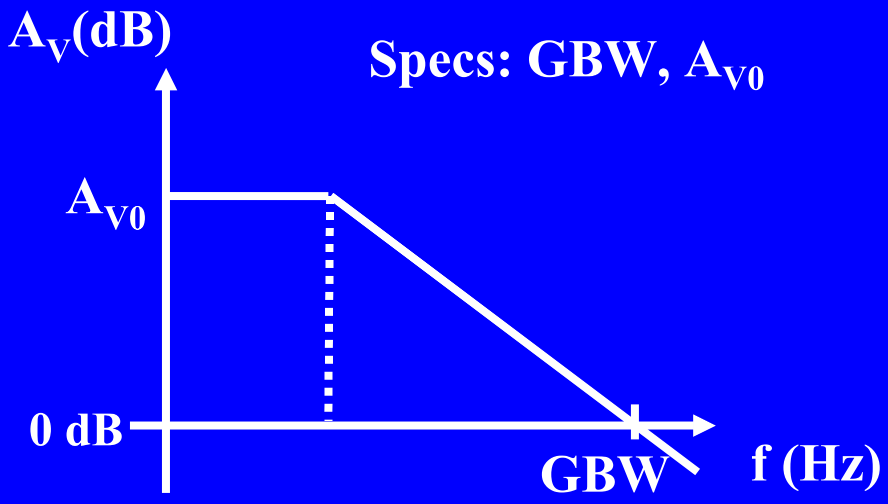
For large V_D, $I_R \ll I_F$; therefore, $I_D \cong I_F$

Equations for Circuit Design



Design parameters→ I_D, W, L

Specs: GBW, A_{V0}



$$I_D = n\phi_t g_m \frac{1+\sqrt{1+i_f}}{2}$$

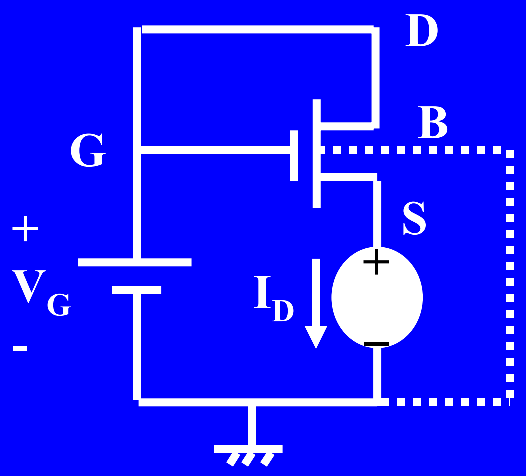
$$L = A_{V0} \frac{n\phi_t}{V_E} \frac{1+\sqrt{1+i_f}}{2}$$

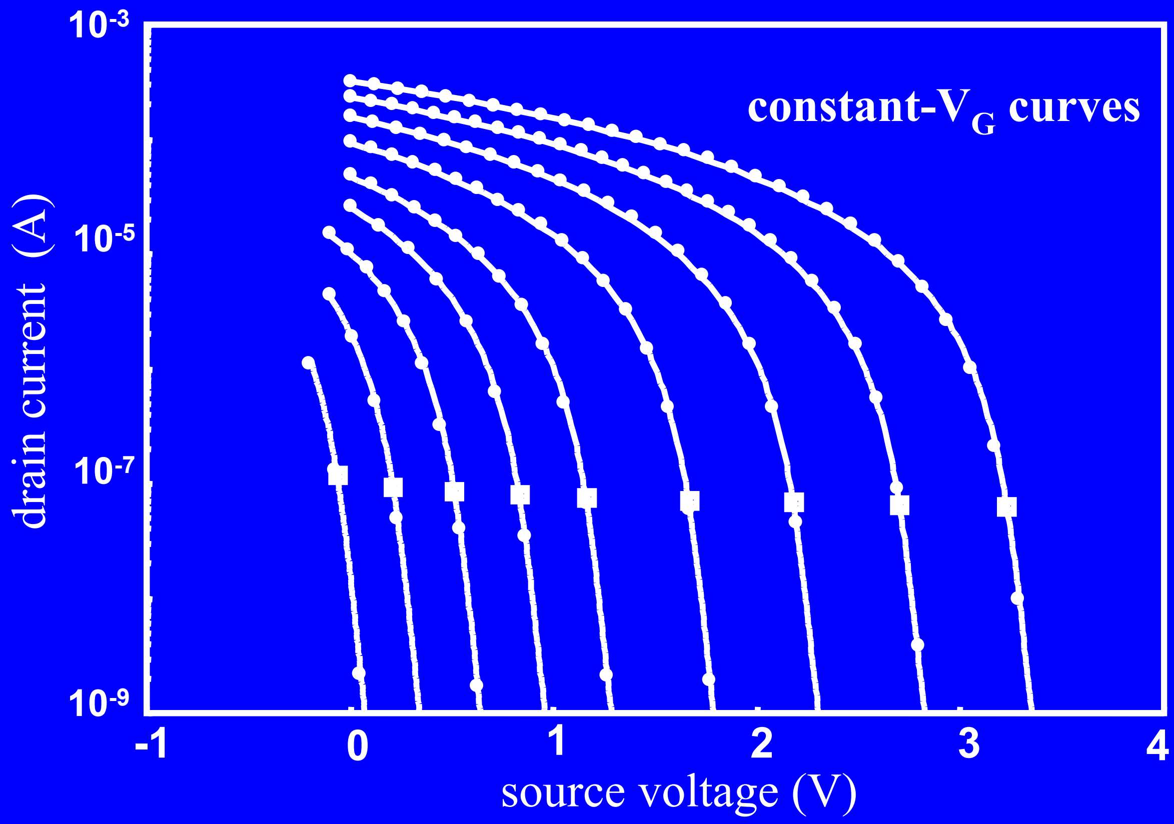
$$\frac{W}{L} = \frac{g_m}{\mu C'_{ox}\phi_t} \frac{1}{\sqrt{1+i_f}-1}$$

$$GBW = g_m / 2\pi C_L \qquad A_{V0} = g_m / g_o$$

Parameter Extraction

Principle for the extraction of I_S, V_T, and n →The percent variation of the drain current wrt the source voltage depends on $i_f = I_D/I_S$





Short-Channel Effects

- **DIBL : drain-induced barrier lowering**

$$I_D = f(V_P, V_S) - f(V_P, V_D)$$

$$V_P(V_G, V_S, V_D) = V_{P0}(V_G) + \frac{\sigma}{n}(V_D + V_S)$$

V_{P0} ⇒ long-channel pinch-off voltage

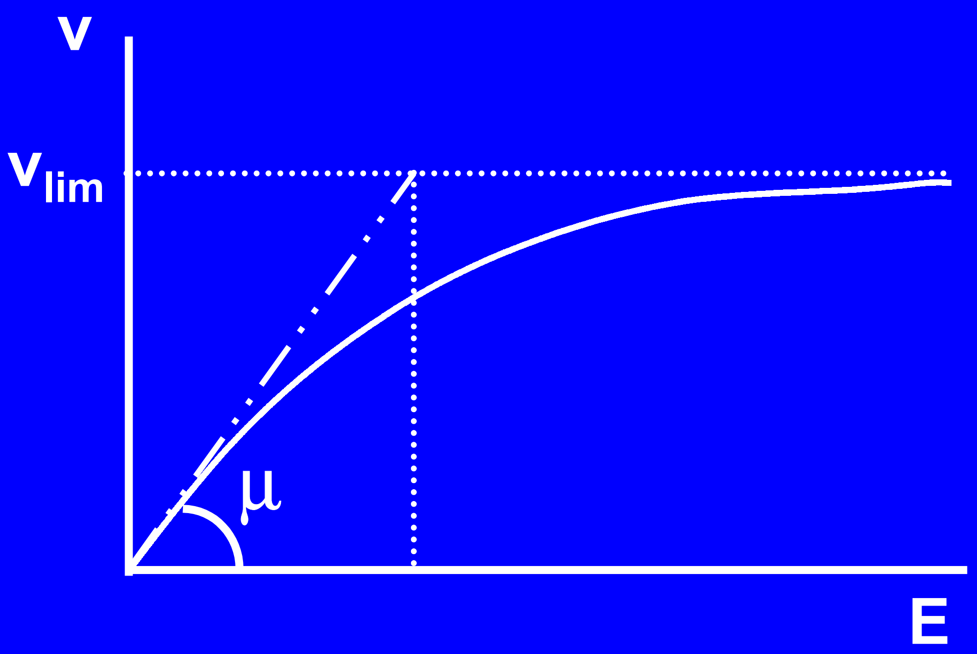
σ ⇒ fitting parameter (depends on technology and L)

• Velocity saturation

$$\boxed{\mu_s = \frac{\mu}{1 + \frac{\mu}{v_{lim}} \frac{d\phi_s}{dx}}}$$

$$\frac{d\phi_s}{dx} = -E$$ **(longitudinal field)**

v_{lim} = 5x10^6 to 2x10^{7}cm/s

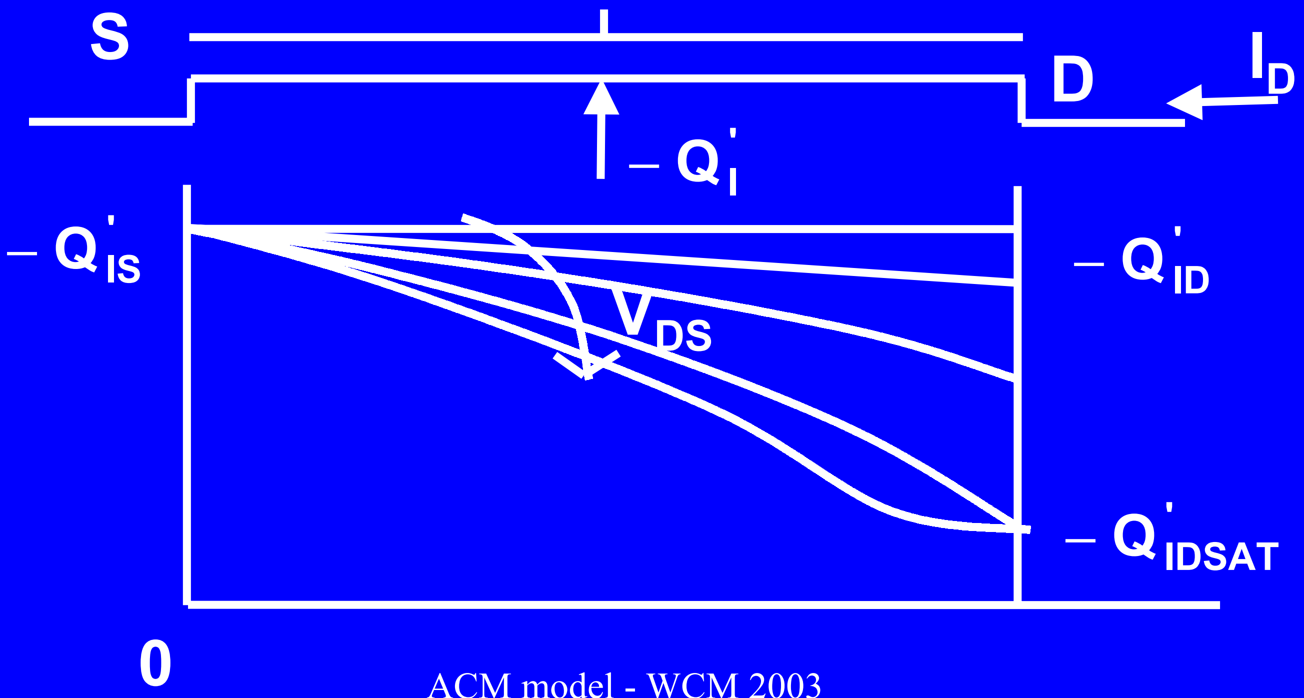


•Velocity saturation (continued)

Saturation:

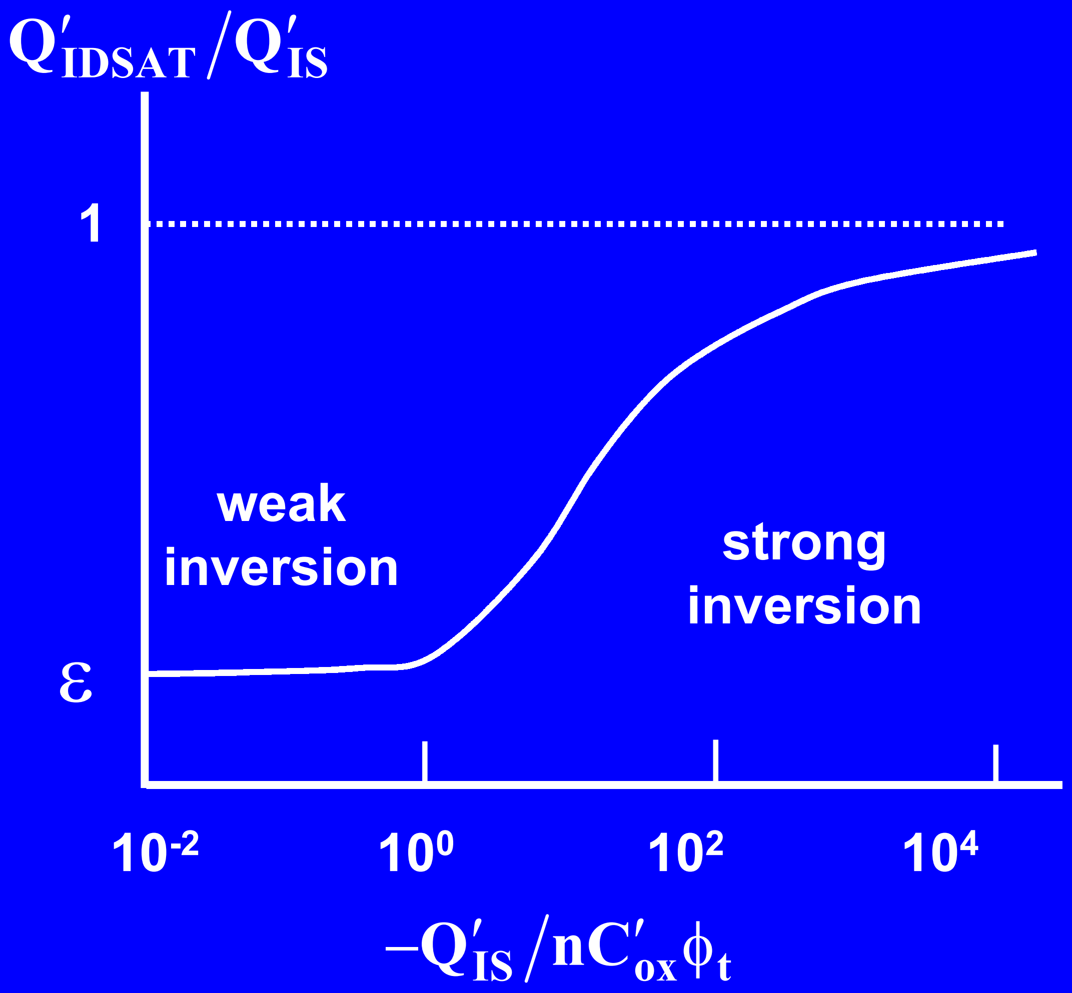
The minimum amount of electron charge flowing at the saturation velocity required to sustain the current is:

$$\boxed{Q'_{IDSAT} = -I_D / W v_{lim}}$$



•Velocity saturation (continued)

$$\varepsilon = \frac{\phi_t / L}{v_{lim} / \mu}$$



•Effects of DIBL and velocity saturation on intrinsic charges

$\mathbf{V_P}$ **includes DIBL** $\rightarrow$ $\mathbf{Q'_{IS(D)}}$ **includes DIBL**

$$\boxed{\mathbf{charge = f\left(Q'_{IS}, Q'_{ID}\right)}}$$

Drift

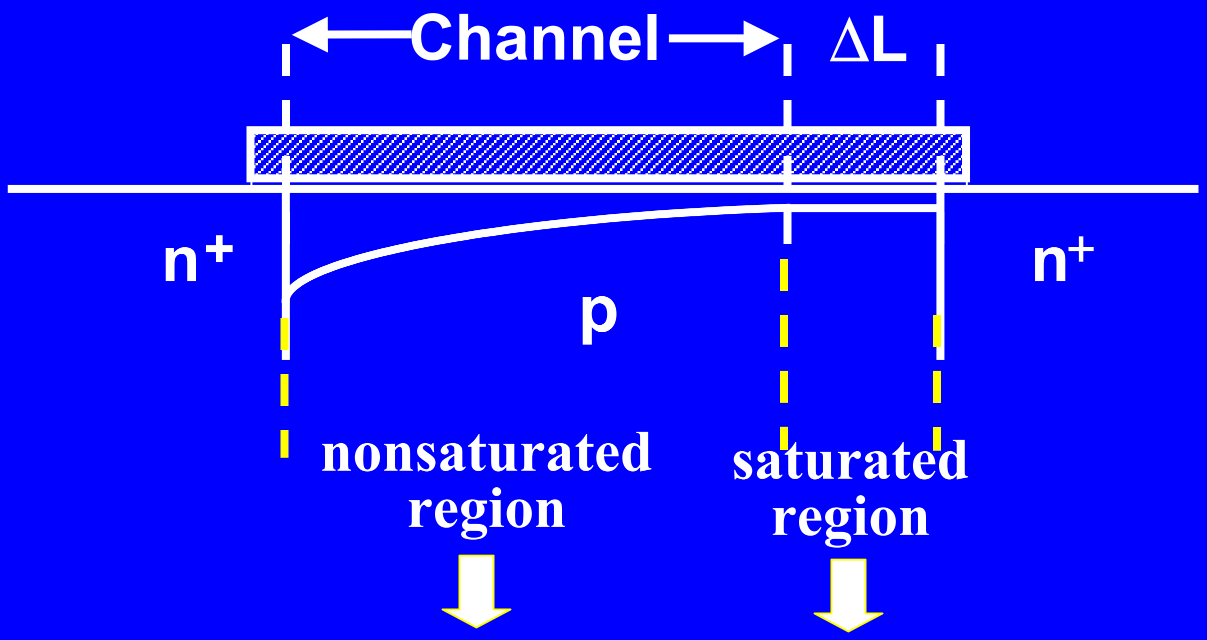
$$\boxed{\mathbf{charge = f\left(Q'_{IS} - nC'_{ox}\phi_t, \cdots\right)}}$$

Drift and diffusion

$$\boxed{\mathbf{charge = f\left(Q'_{IS} - nC'_{ox}\phi_t + \frac{I_D}{W_{eff}\,v_{lim}}, \cdots\right)}}$$

Drift, diffusion and velocity saturation

•Short-channel effects on intrinsic charges



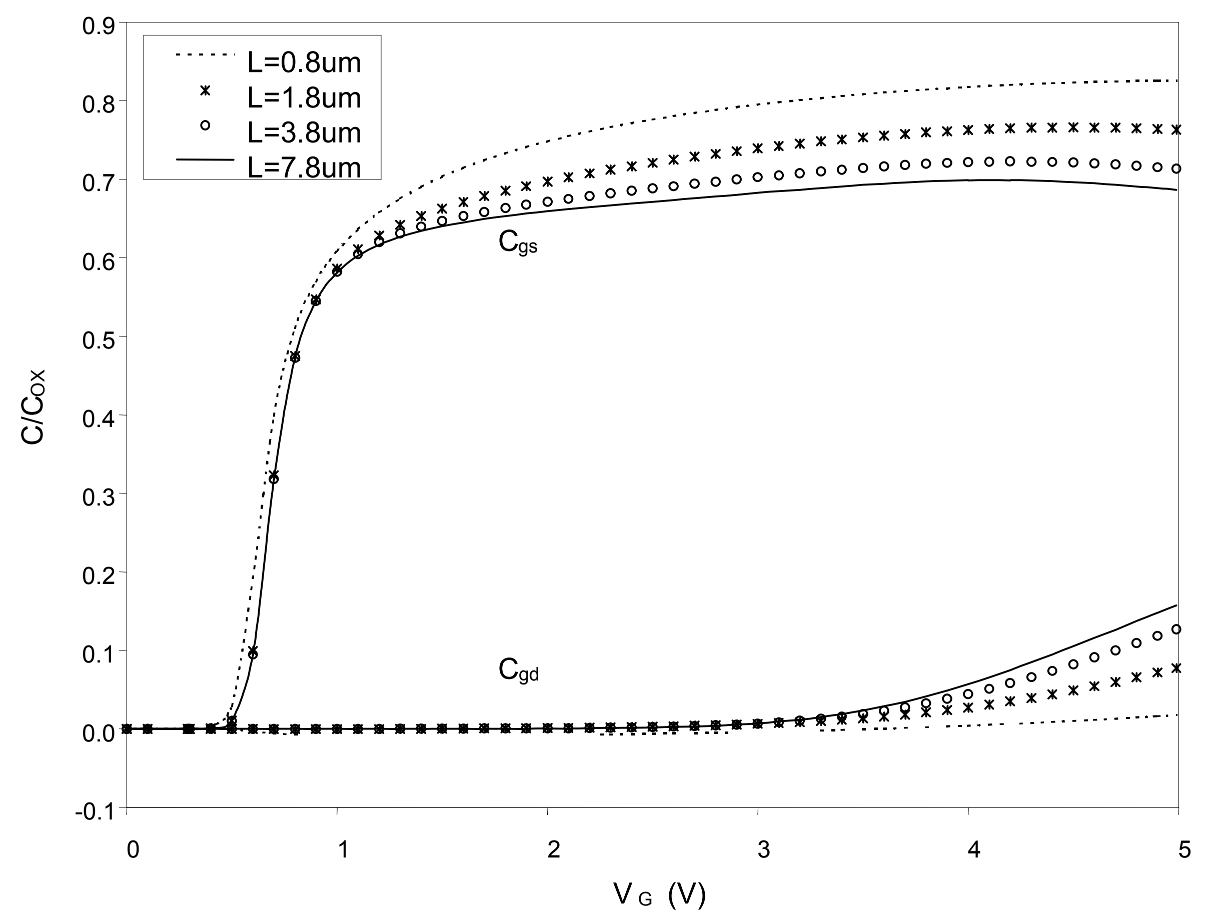
nonsaturated region

saturated region

$$Q_I = W_{eff}\int_0^{L_{eq}} Q_I' dx + W_{eff}\Delta L Q'_{IDSAT}$$

$$Q_I = W_{eff}L_{eff}\left(\frac{2}{3}\frac{Q_F'^{2} + Q_F' Q_R' + Q_R'^{2}}{Q_F' + Q_F'} - Q'_{IP} + Q'_{IDSAT}\right) + W_{eff}\Delta L Q'_{IDSAT}$$

$$Q'_{F(R)} = Q'_{IS(D)} + Q'_{IP} - Q'_{IDSAT}$$



C_{gs} and C_{gd} versus V_G for channel-lengths varying from 0.8μm to 7.8μm. V_D=5V and V_S=V_B=0V.

ACM Model for Simulators

Parameter	Description	Unit
VTO	Zero-bias threshold voltage	V
GAMMA	Body-effect parameter	$V^{1/2}$
PHI	Surface potential	V
TOX	Gate oxide thickness	m
LD	Lateral diffusion	m
XJ	Junction depth	m
UO	Low-field mobility	cm^2/Vs
VMAX	Saturation velocity	m/s
THETA	Mobility reduction parameter	V^{-1}
SIGMA	DIBL parameter	m^2
PCLM	CLM parameter	-

The ACM model is available in SMASH, a circuit simulator of Dolphin Integration

Summary

Properties of the ACM model:

- MOSFET model based on physics
- Appropriate normalization variables that represent the physics behind the model

Normalization variable	Symbol	Definition
Thermal voltage	ϕ_t	$k_B T/q$
Pinch-off charge density	Q'_{IP}	$-nC'_{ox}\phi_t$
Specific current	I_S	$n\mu C'_{ox}(\phi_t^2/2)(W/L)$
Channel length	L	L
Transit time	τ	$L^2/(2\mu\phi_t)$

Summary (continued)

- Single-piece expressions with infinite order of continuity
- Preserves the MOSFET symmetry
- Conserves charge
- Reduced number of parameters
- Implemented in SMASH, a mixed-mode simulator