The direct determination of MOSFET parameters from the I_D versus V_S curve at low V_{DS}

Carlos Galup-Montoro, Márcio Bender Machado,
Thiago de Oliveira, Márcio Cherem Schneider

UFSC

Federal University of Santa Catarina
Brazil

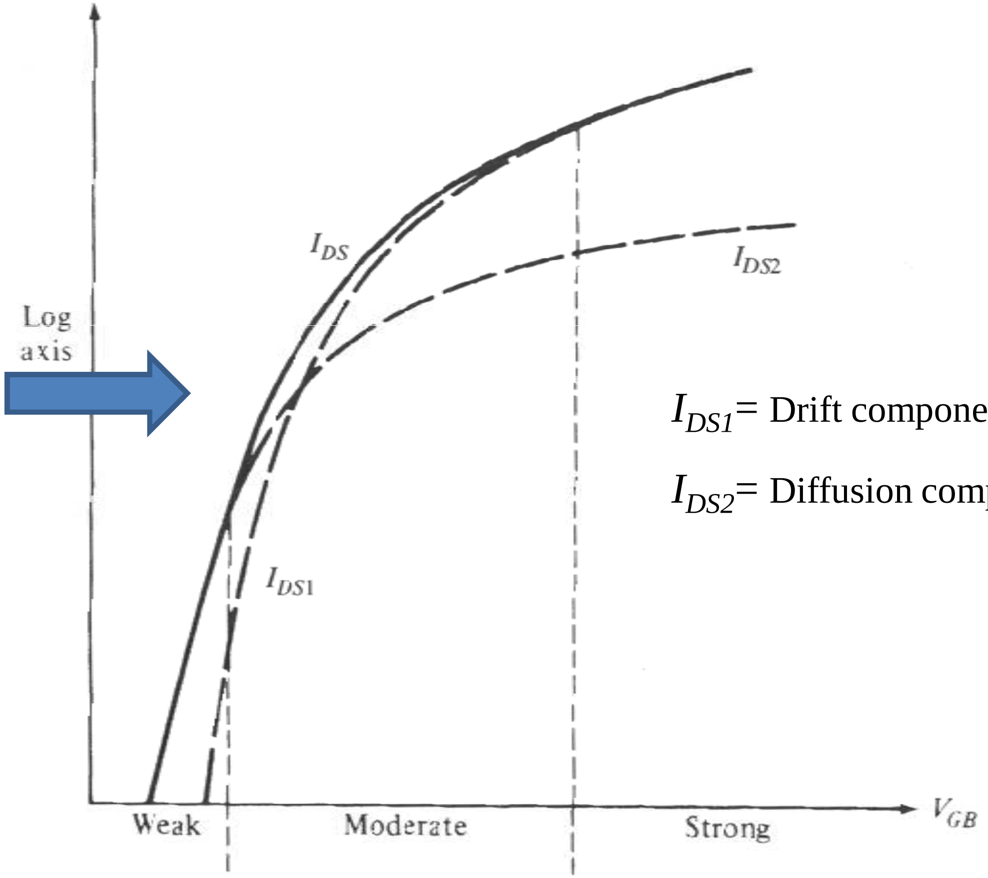
MOS-AK Workshop, December 2010

Contents

Threshold voltage (VT)

Near the threshold condition (moderate inversion), both the drift and diffusion transport mechanisms are important.

No critical point can be directly identified



I_{DS1}= Drift component

I_{DS2}= Diffusion component

* *from Yannis Tsividis, Operation and Modeling of The MOS transistor, MCGraw-Hill*

Classical threshold voltage (VT) definition

Classical (surface potential based) definition of threshold:

$$\phi_S = 2\phi_F + V_C$$

Where : ϕ_S - surface potential for $V_G=V_T$

ϕ_F - Fermi potential in the substrate

V_C - channel potential

In principle the direct determination of the threshold voltage is possible

1) calculate the saturation drain current $\mathbf{I_{DTh}}$ for $\phi_S = 2\phi_F + V_C$

2) inject $\mathbf{I_{DTh}}$ in the transistor and measure $\mathbf{V_G = V_T}$

Drawbacks

- geometrical (W, L) and technological parameters (mobility, oxide thickness,..) are needed to calculate $\mathbf{I_{DTh}}$
- the transistor operates in the saturation region where several secondary effects are relevant

Current based threshold definition

$V_T \equiv V_G$, when $I_{drift} = I_{diff}$

For a MOSFET the current defined threshold corresponds to an inversion charge density equal to the thermal charge density (the effective channel capacitance per unit area times the thermal voltage).

For a bulk MOSFET

$$Q'_I = -nC'_{OX}\,\phi_t$$

where n *is the slope factor*

Relationship between threshold voltages

Threshold Definition	Physical Meaning	Value of ϕ_S at threshold	Value of Q_I' at threshold	Difference in V_{T0} relative to classical definition
$\phi_S = 2\phi_F + V_C$	Surface concentration of electrons= bulk concentration of holes	$2\phi_F + V_C$	$-(n-1)C'_{ox}\phi_t$	0
$Q_I' = -nC'_{ox}\phi_t$	50% drop (relative to the peak) in the g_m/I_D curve	$2\phi_F + V_C + \phi_t \ln\left(\frac{n}{n-1}\right)$	$-nC'_{ox}\phi_t$	$\phi_t\left[1 + n\ln\left(\frac{n}{n-1}\right)\right]$

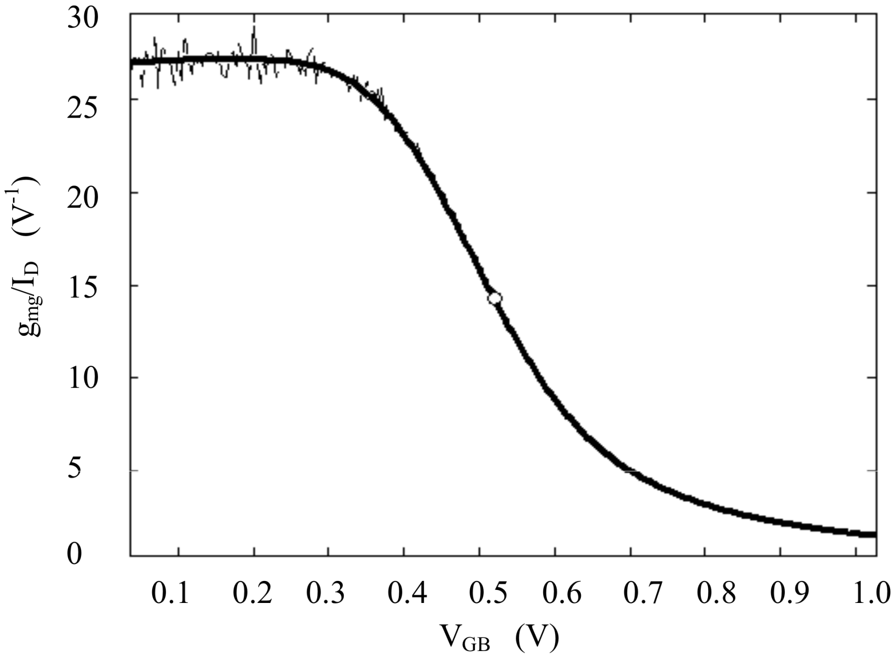
‘Ideal’ threshold voltage extraction procedure

- No parameters are needed to calculate the threshold current
- The transistor operates at low current levels and in the linear region to minimize series resistances and short channel effects

⇓

gm/Id curve in the linear region

VT determination from gm/Id curve in the linear region



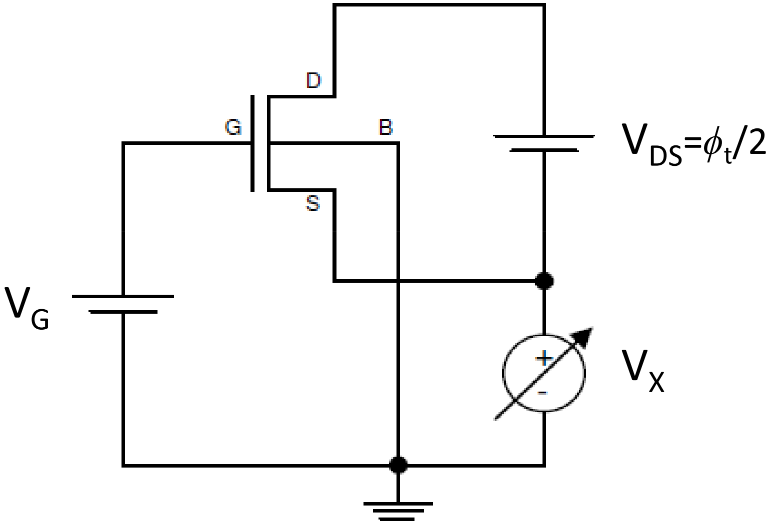
- Transconductance-to-current ratio for $V_{DS} \cong \phi_t/2$ and $V_S=0$.

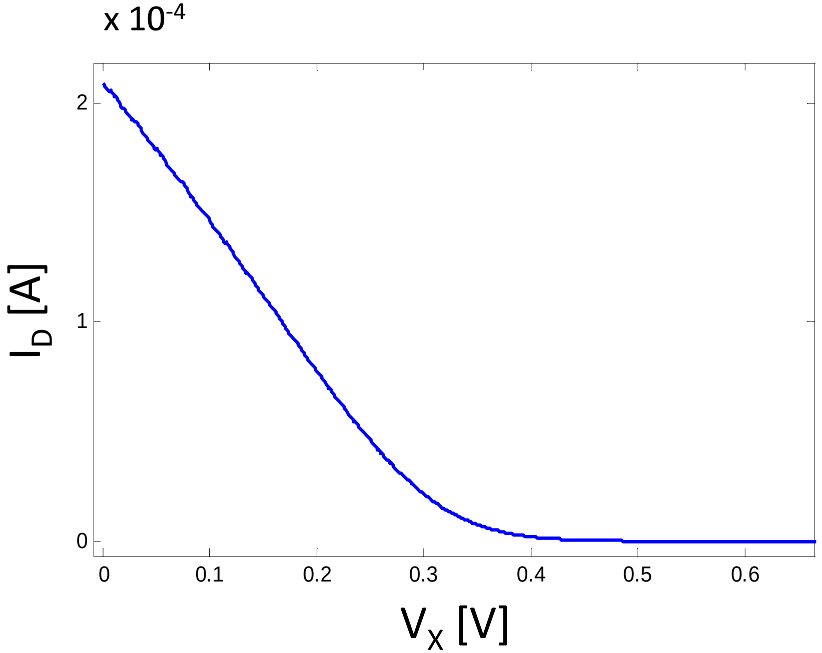
Threshold $g_m/I_D \cong 0.5\ (g_m/I_D)_{max}$

Drawback $(g_m/I_D)_{max}$ has some dependence on V_G

The new (channel conductance G_{n0}/Id) methodology

Direct determination of MOSFET parameters from the ID versus VS curve at low VDS





$$\Delta V_S = \Delta V_D = \Delta V_X$$

$$\frac{\partial I_D}{\partial V_X} = -g_{ms} + g_{md} = G_{no}$$

The Gn0/Id methodology

Transistor operation:

- low V_{DS}
- weak and moderate inversion
- fixed V_G

Negligible effects of :

- series resistances
- field dependent mobility
- slope factor variation
- channel length modulation

The Gn0/Id methodology – extract V_T and I_S

From transistor model

$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1+i_{f(d)}}-1\right)$$

$$I_D = I_S\left(i_f - i_r\right) \qquad I_S = \mu C'_{OX}\, n \frac{\phi_t^{\,2}}{2}\frac{W}{L}$$

$$\frac{G_{n0}}{I_D} = \frac{-2}{\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)} = \left(\frac{G_{n0}}{I_D}\right)_{\min}\frac{2}{\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

From UICM

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

When $i_f=3 \rightarrow V_P=V_S=V_X$

When

for $i_f = 3$ and

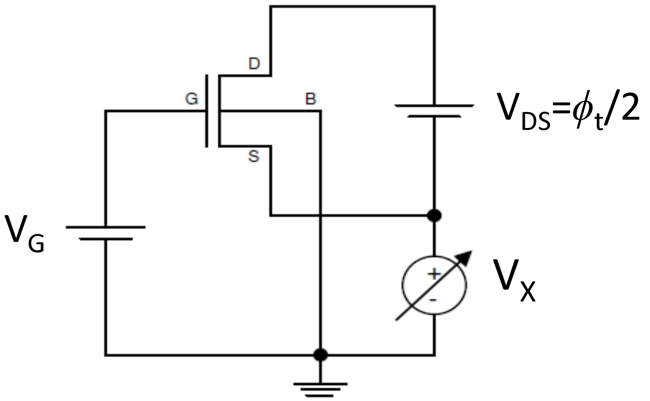
$V_{DS} = \phi_t /2$

we have $i_r = 2.12$

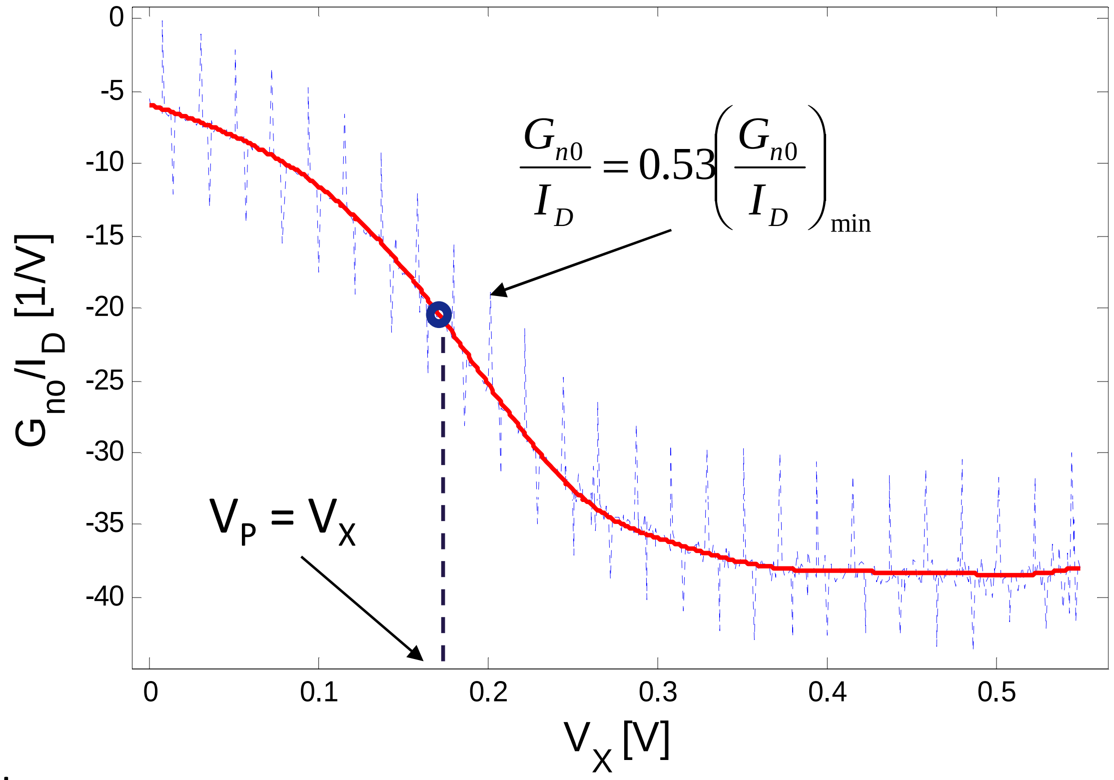
$$\frac{G_{n0}}{I_D} = 0.53*\left(\frac{G_{n0}}{I_D}\right)_{\min}$$

and

$$V_P = V_X$$



The Gn0/Id methodology – extract V_T and I_S



When

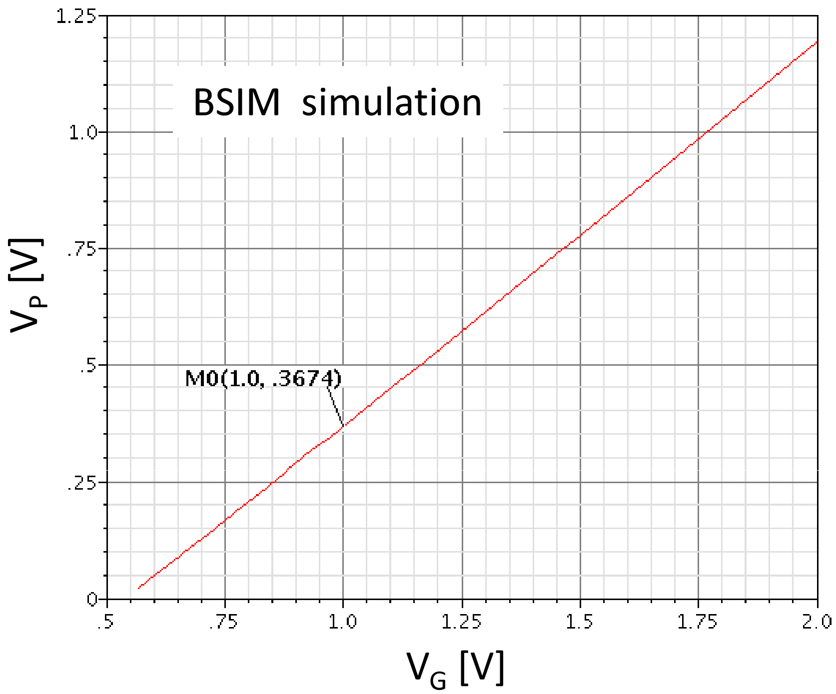
$$\frac{G_{n0}}{I_D} = 0.53*\left(\frac{G_{n0}}{I_D}\right)_{\min}$$

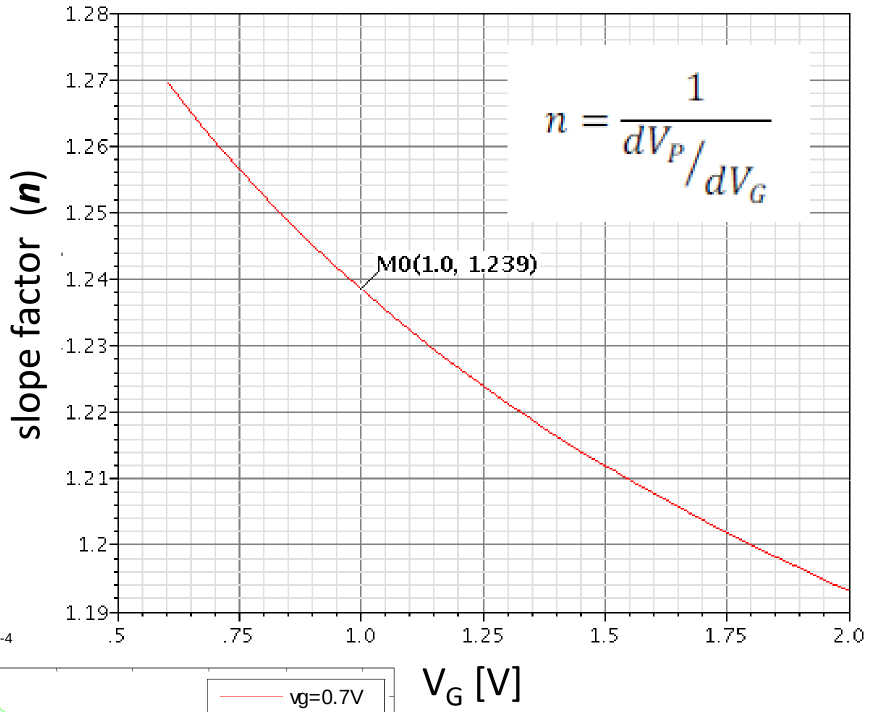
$$V_{T0} = -\,nV_P + V_G$$

and

$$I_S = I_D$$

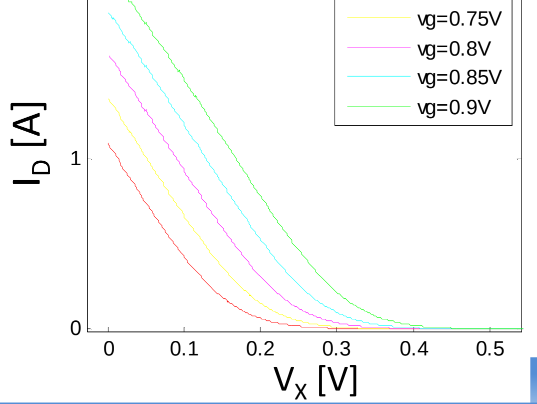
The Gn0/Id methodology – extract pinch-off voltage V_P and slope factor *n*



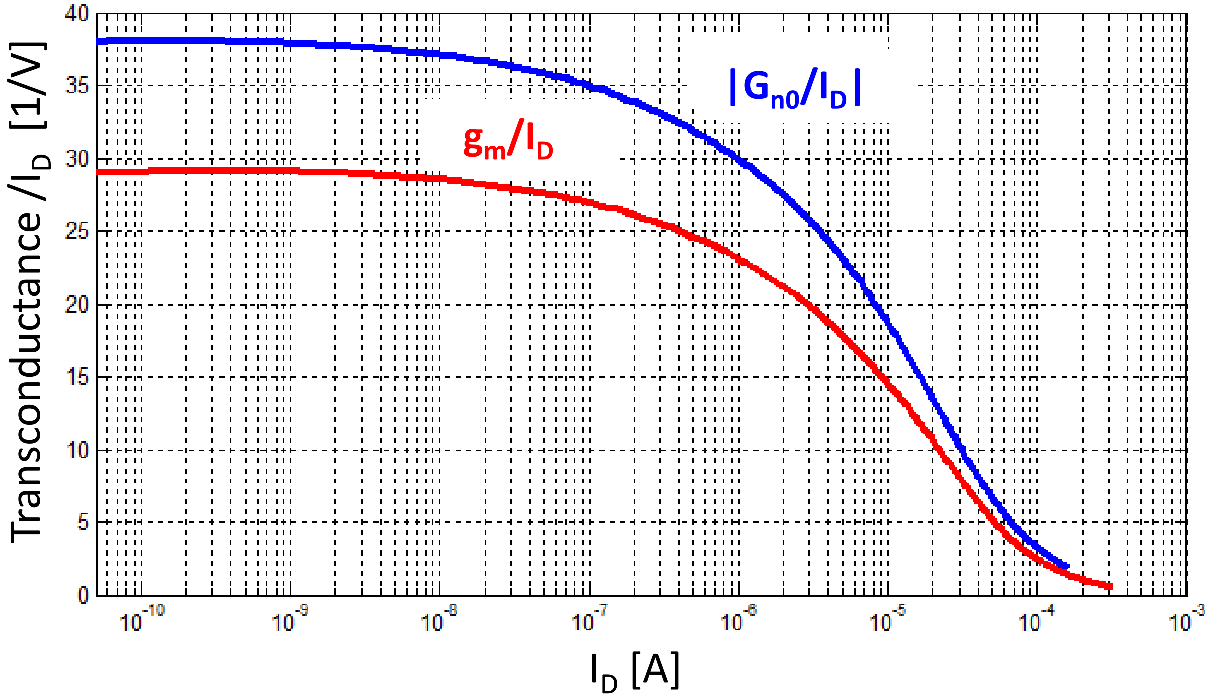


$$n = \frac{1}{dV_P/dV_G}$$

measuring I_D x V_S for different V_G values



Gn0/Id x gm/Id methods



$$\frac{g_{mg}}{I_D} = \frac{2}{\boxed{n\phi}_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

$$\frac{G_{no}}{I_D} = \frac{-2}{\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

Gn0/Id x gm/Id methods

0.18 μm technology

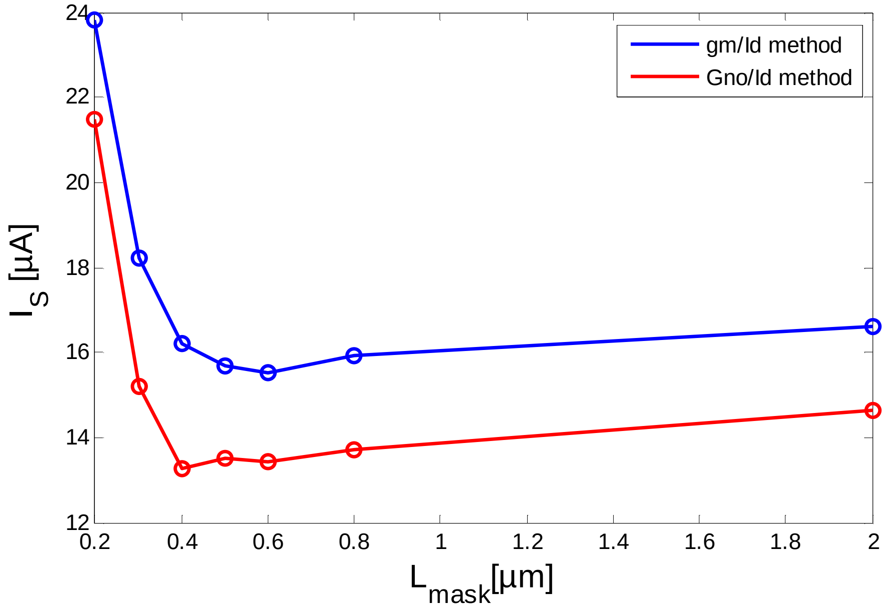
V_{T0}

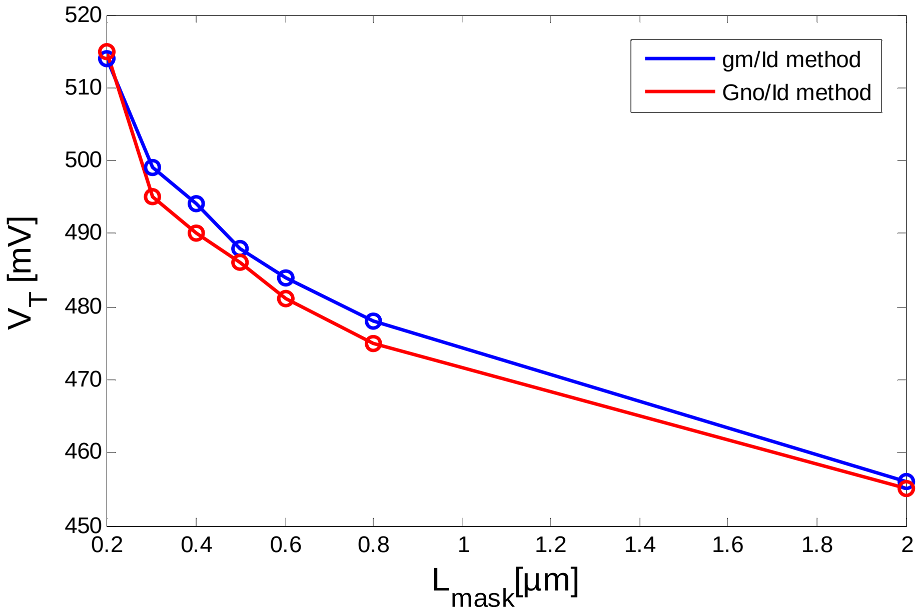
L_{mask} (W/L=100)	0.2 μm	0.3 μm	0.4 μm	0.5 μm	0.6 μm	0.8 μm	2.0 μm
V_T (mV) gm/I_D	514	499	494	488	484	478	456
V_T (mV) Gn0/I_D	515	495	490	486	481	475	455

I_S

L_{mask} (W/L=100)	0.2 μm	0.3 μm	0.4 μm	0.5 μm	0.6 μm	0.8 μm	2.0 μm
I_S (μA) gm/I_D	23.82	18.21	16.19	15.67	15.54	15.94	16.62
I_S (μA) Gn0/ID	21.47	15.21	13.27	13.53	13.41	13.72	14.65

I_S when $V_{GS} \approx V_{T0}$





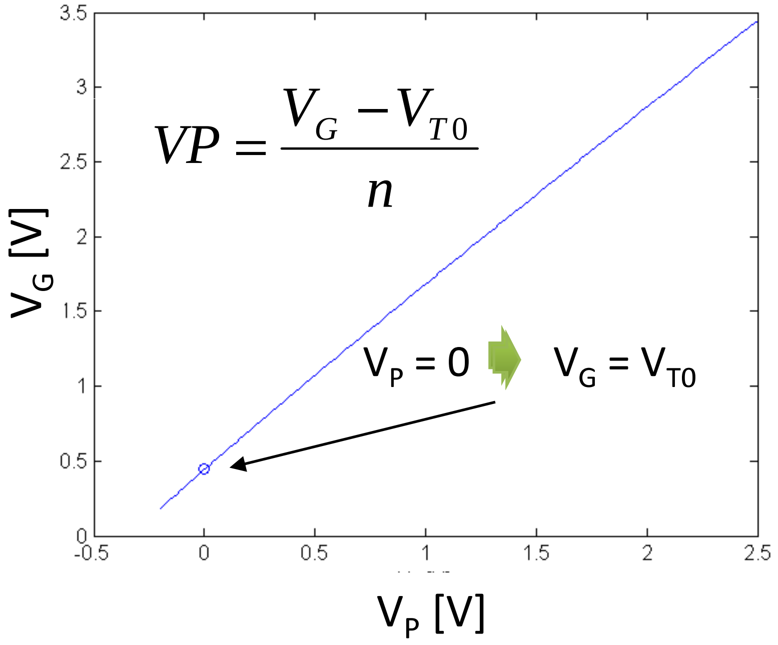
Applications

Applications using VT extraction

- Transistor aging (or electrical stress)
- Matching assessment
- Temperature drift characterization
- Radiations effects on MOS transistor

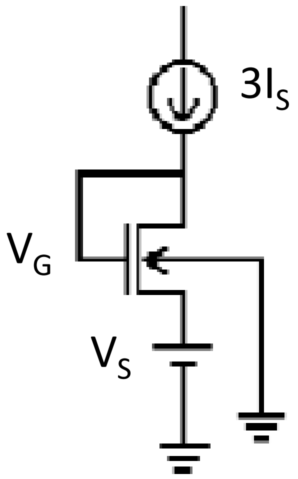
Applications

1- Extract IS and VT in a non-noisy environment using an accurate method (gm/Id or Gn0/Id)



$$VP = \frac{V_G - V_{T0}}{n}$$

2- Extract VT in a real environment considering Id=3*Is (i_f=3) in a saturated transistor

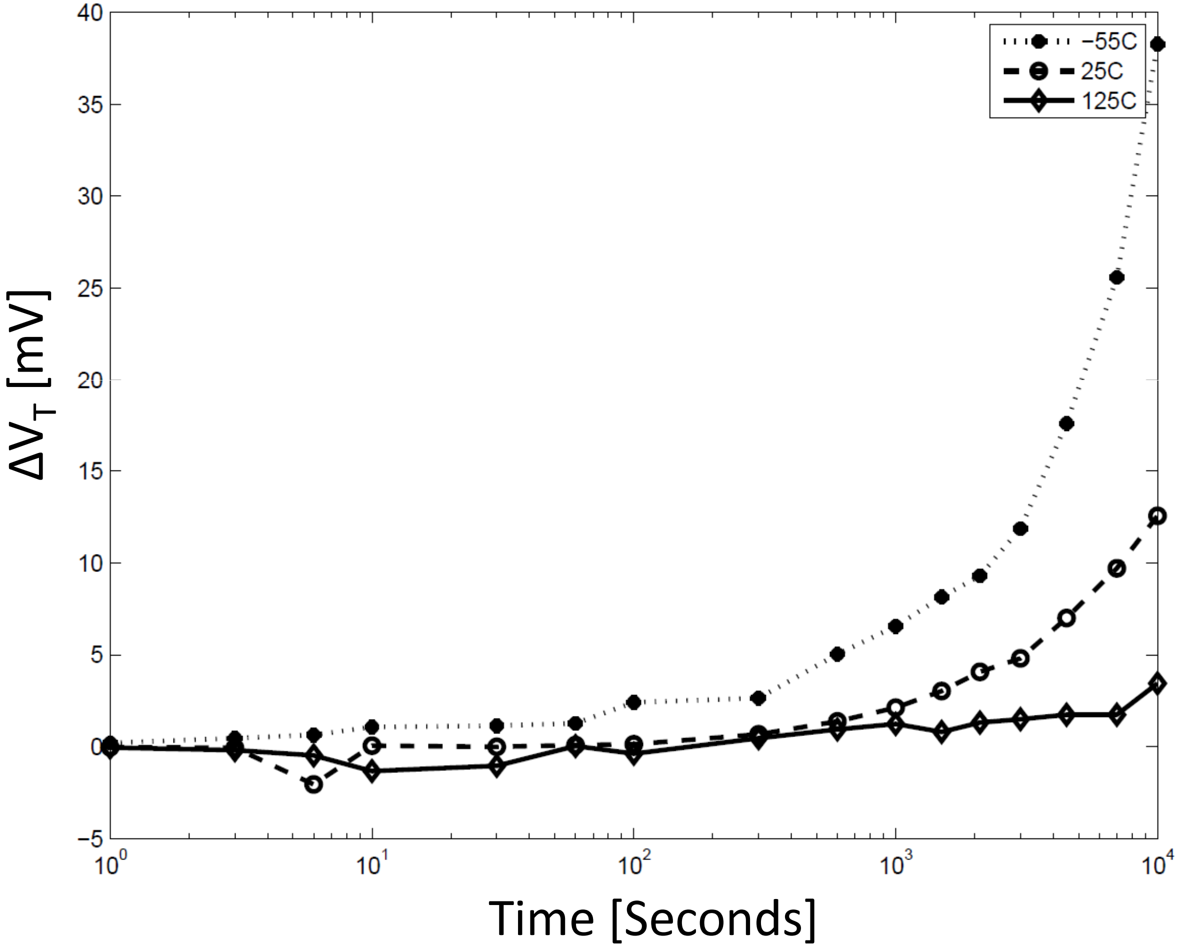


From UICM

when $i_f = 3$, $V_P = V_S$

Applications

Example of HCI stress measurement using VT variation



Conclusions

- New procedure for direct determination of the threshold voltage and some other important electrical parameters with minimum influence of second order effects.
- The threshold voltage is determined at a constant gate-to-substrate voltage, at a low drain-to-source voltage and with transistor operation in the weak and moderate inversion regions.
- Under these operating conditions the effects of series resistances, mobility and slope factor variations, and channel length modulation are practically negligible, allowing a direct determination of the threshold voltage and of the DIBL effect.