MOSFET Threshold Voltage: Definition, Extraction, and Applications

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Classical threshold voltage (V_T) 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 $\phi_S = 2\phi_F + V_C$

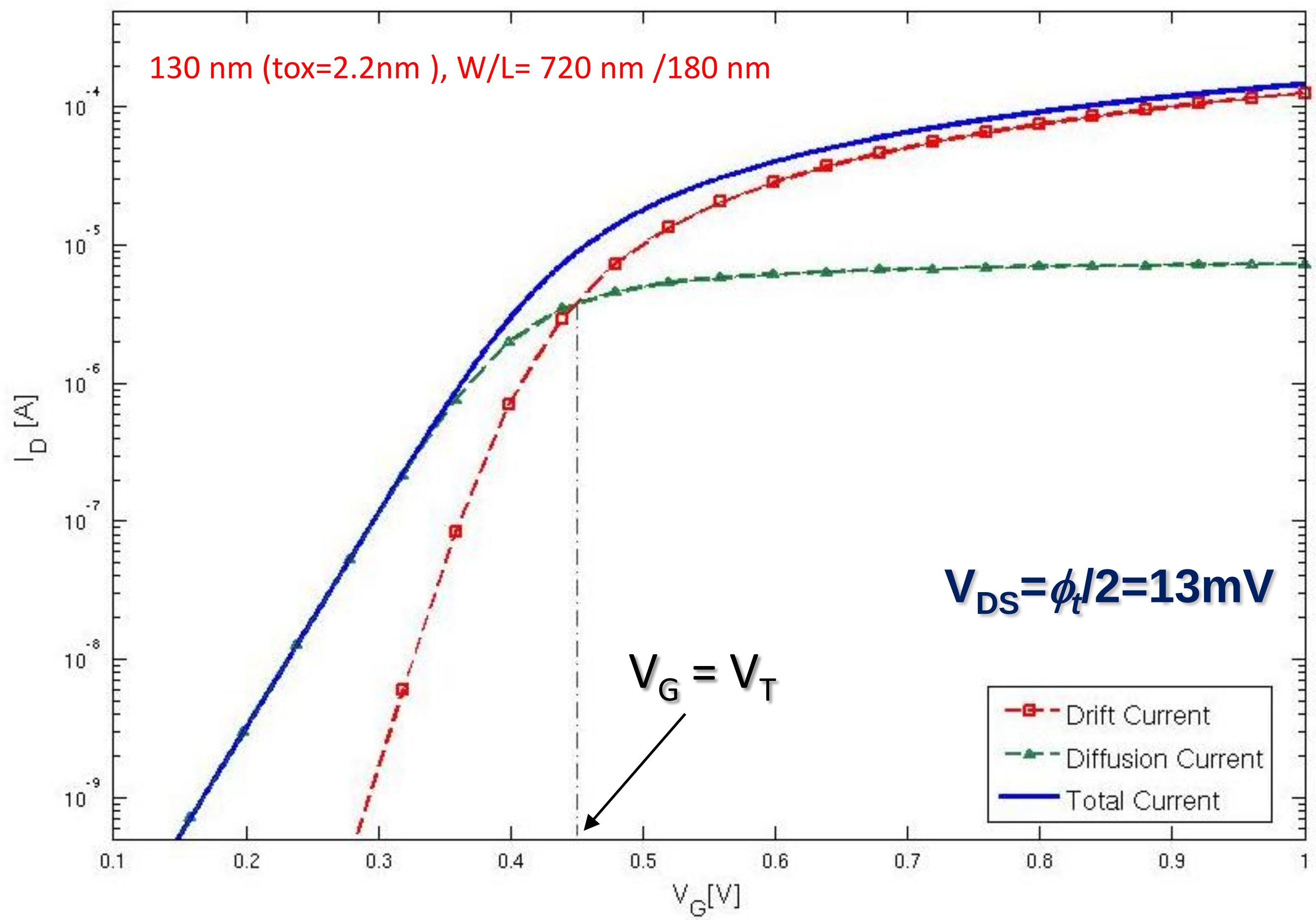
2) inject $\mathbf{I_{DTh}}$ into the transistor and measure $\mathbf{V_G = V_T}$

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

Threshold voltage is defined as the gate voltage at which the condition $I_{drift} = I_{diff}$ holds.



Classical vs. current-based definitions

	Physical Meaning	Value of ϕ_s at threshold	Value of Q_I' at threshold	Difference in V_T relative to the classical definition
Classical	Surface concentration of electrons= bulk concentration of holes	$2\phi_F + V_C$	$-(n-1)C'_{ox}\phi_t$	0
x Current based	Drift component = Diffusion component of drain current	$2\phi_F + V_C + \phi_t \ln\left(\frac{n}{n-1}\right)$	$-nC'_{ox}\phi_t$	$\phi_t\left[1+n\ln\left(\frac{n}{n-1}\right)\right]$

n is the slope factor given by

$$n = 1 + \left(\frac{C'_b\,(V_{GB})}{C'_{ox}}\right)$$

where

C'_{ox} is the oxide capacitance per unit area

C'_b is the depletion capacitance per unit area

‘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
- Fixed V_{GB} to avoid variation in the slope factor

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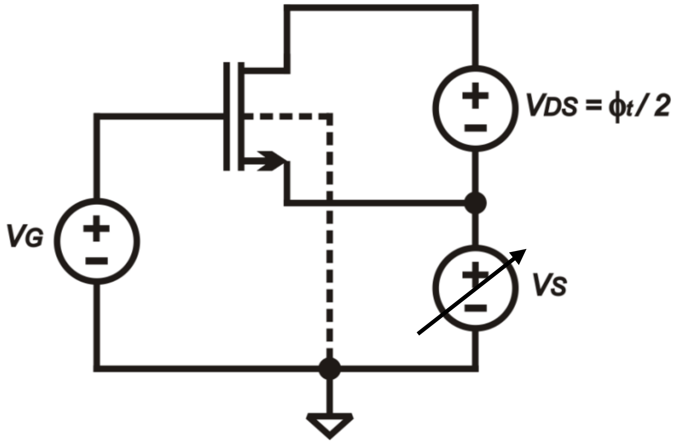
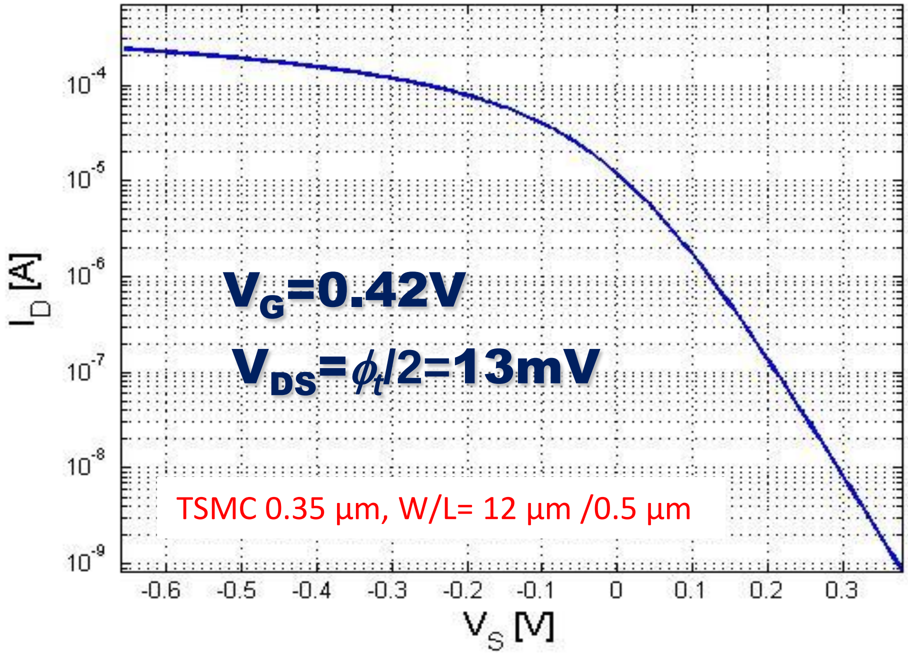
g_{ds}/I_D procedure

The g_{ds}/I_D procedure

Direct determination of MOSFET parameters from the I_D vs V_S curve at low V_{DS} (linear region)





$$\Delta I_D = -g_{ms}\Delta V_S + g_{md}\Delta V_D$$

The g_{ds}/I_D methodology – extraction of V_T and I_s

From transistor model

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

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

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

$$\frac{g_{ds}}{I_D} = -\frac{1}{I_D}\frac{dI_D}{dV_S} = \frac{2}{\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

$$\left(\frac{g_{ds}}{I_D}\right)_{\max} = \frac{1}{\phi_t}$$

When

$i_f = 3$

$V_{DS} = \phi_t / 2$

$$\frac{gds}{I_D} = 0.53 * \frac{1}{\phi_t}$$

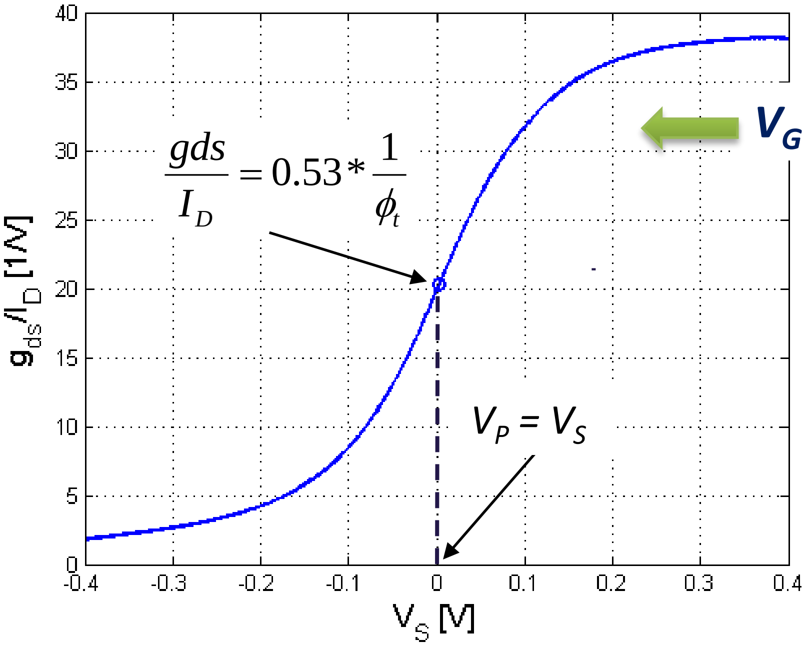
and

$$V_P = V_S$$

$V_{T0} = V_G$ when $V_P = 0$

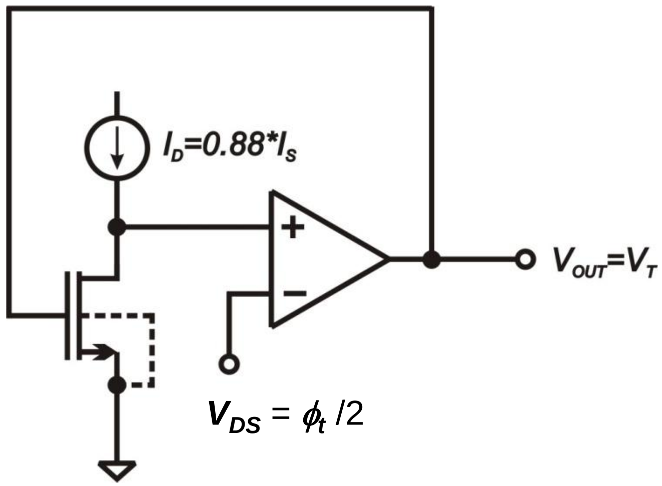
$I_S = 1.14 * I_D$

TSMC 0.35 µm, W/L= 12 µm /0.5 µm



$V_G = V_{T0}$!

Automatic V_T-extractor circuit - based on g_{ds}/I_D procedure



Automatic V_T -extractor circuit

Biasing condition

$V_{DS} = \phi_t /2$ (linear region)

$i_f = 3$

$i_r = 2.12$

$$I_D = I_S(i_f - i_r) = 0.88 I_S$$

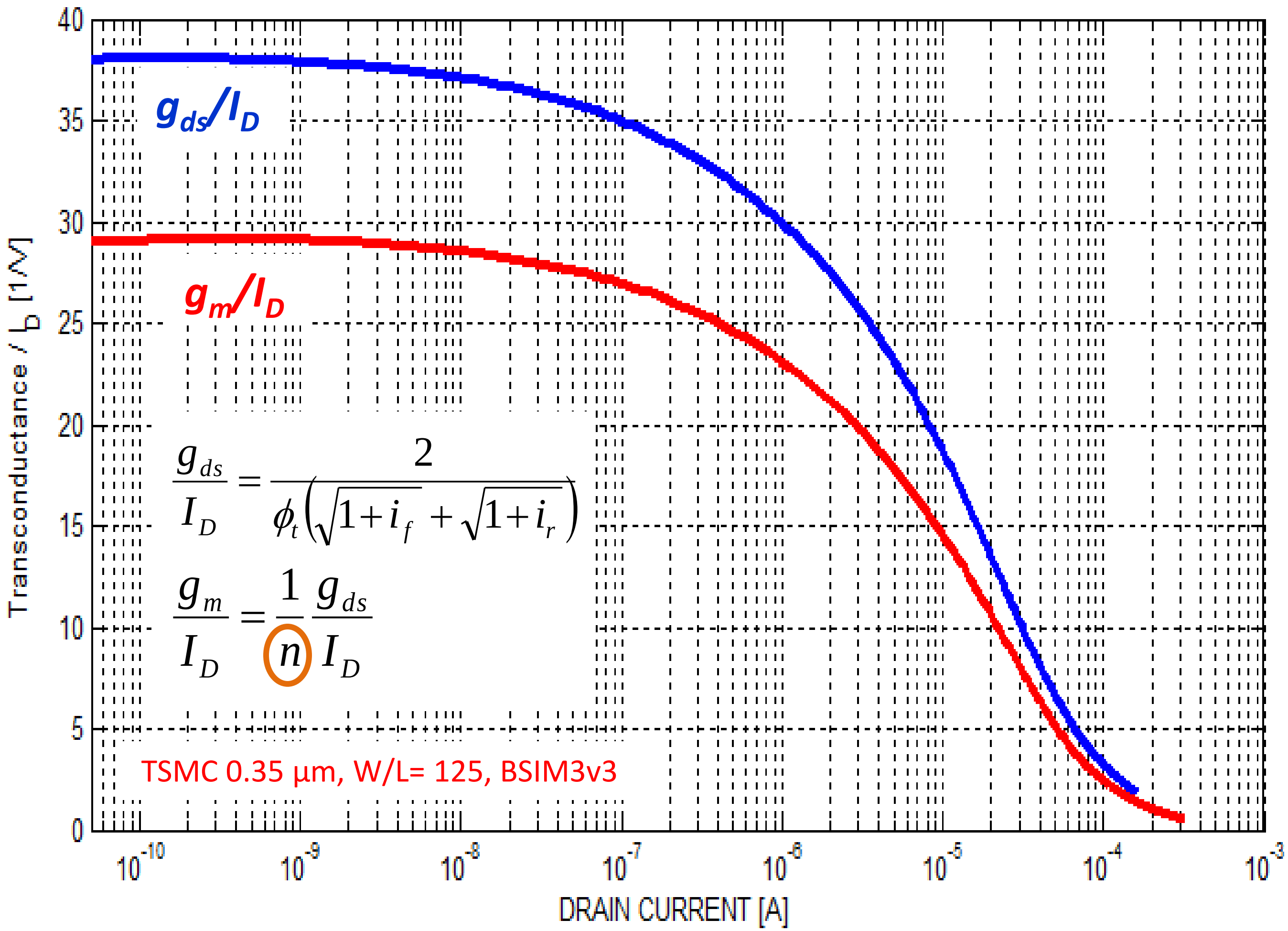
From transistor model

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

$V_P = 0$

$$V_G = V_{T0}$$

g_{ds}/I_D x g_m/I_D methods



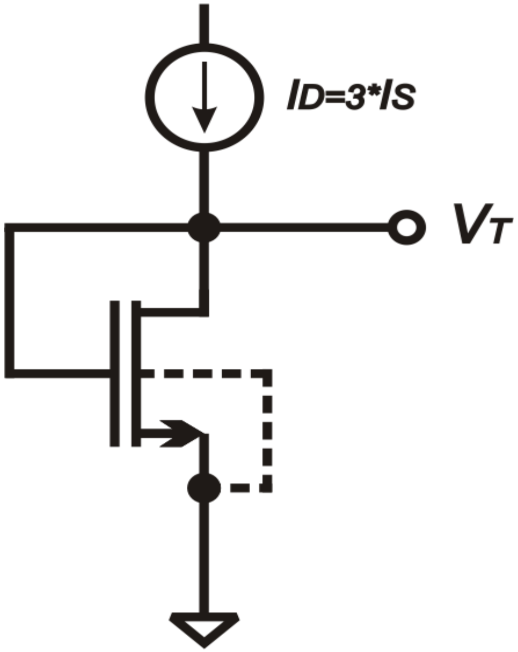
$$\frac{g_{ds}}{I_D} = \frac{2}{\phi_t\left(\sqrt{1+i_f} + \sqrt{1+i_r}\right)}$$

$$\frac{g_m}{I_D} = \frac{1}{n}\frac{g_{ds}}{I_D}$$

g_{ds}/I_D is independent of slope factor (n).

Constant current (CC) method

For a saturated transistor biased with I_D=3*I_S, we have V_G=V_T for V_S=0.



From transistor model

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

$$V_P \cong \frac{V_G - V_T}{n}$$

For

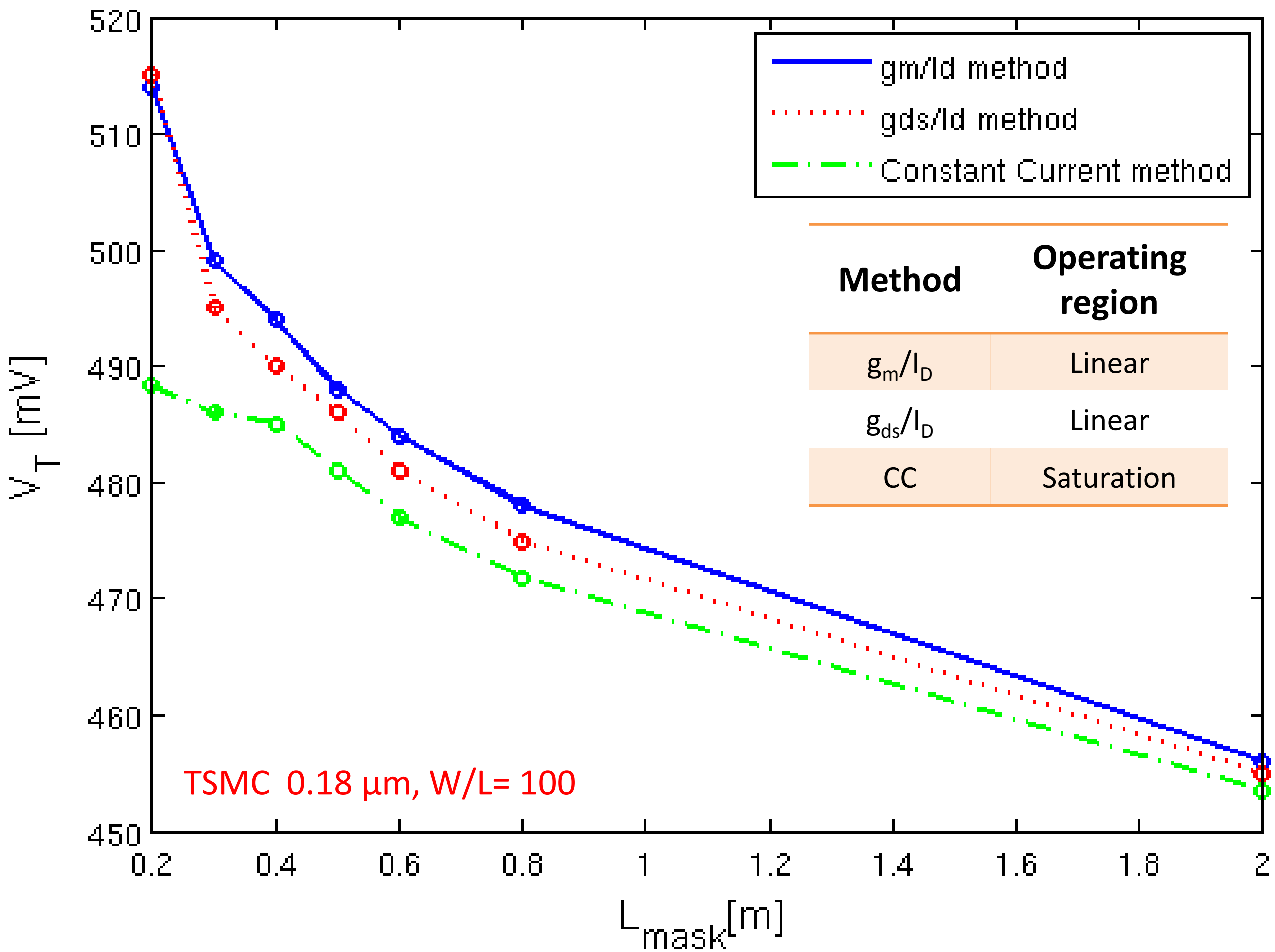
$i_f = 3$

$V_S = 0$

$\Rightarrow$ $V_P=0$ and $V_G=V_T$

The *CC* method was used in a previous V_T-extractor circuit for tracking the V_T variation as a function of a specific parameter, *e.g.* temperature or ionizing radiation.

Measured V_T values vs. L_{mask} for different extraction methods



Method	Operating region
g_m/I_D	Linear
g_{ds}/I_D	Linear
CC	Saturation

These methods present similar behaviors, especially for g_m/I_D and g_{ds}/I_D methods.

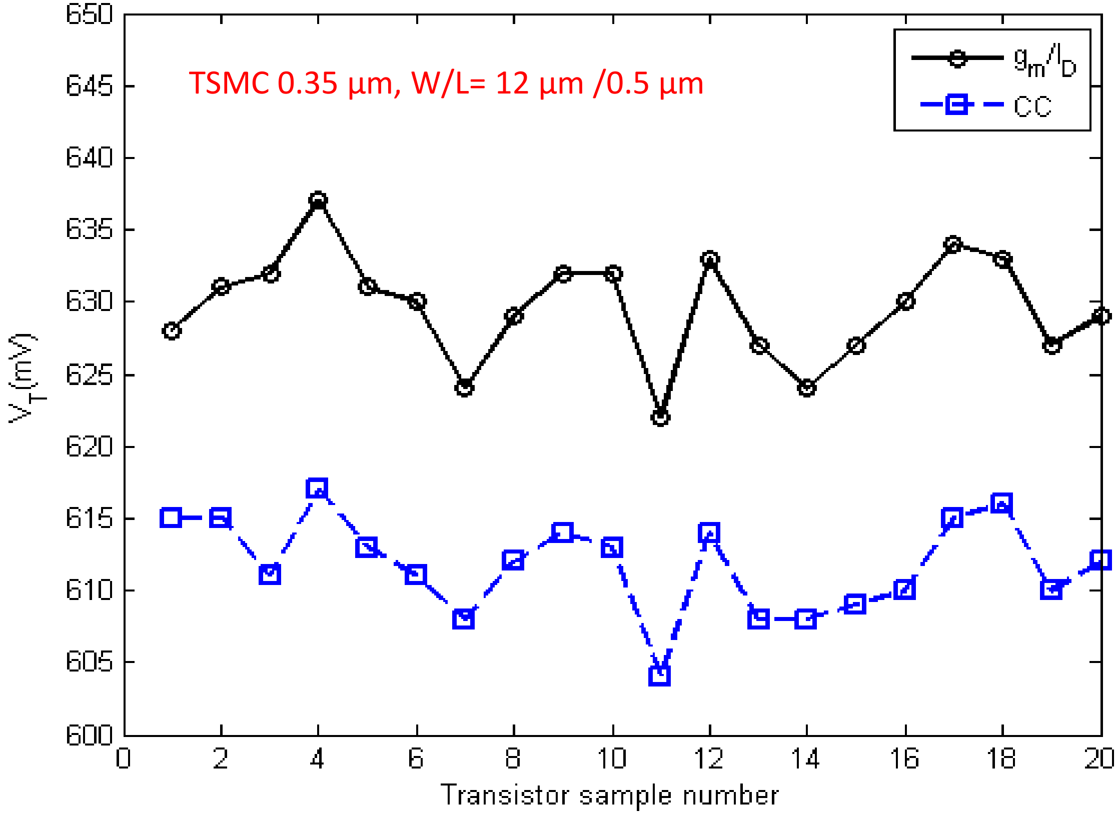
Applications

The threshold voltage is a fundamental electrical parameter that can be used in:

- technology characterization
- aging evaluation
- matching assessment
- temperature and radiation sensors

Example of application:

Matching assesment



V_T average values:

g_m/I_D ⇒ 629mV

CC ⇒ 611.5mV

Relative standard deviation

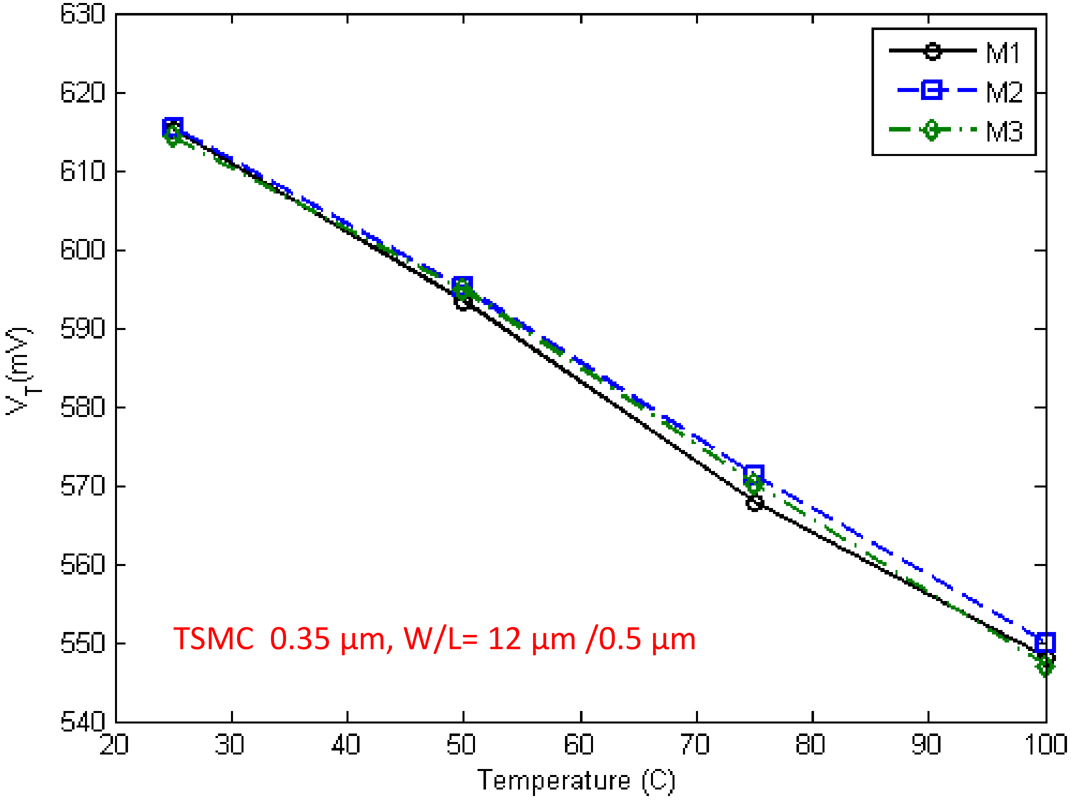
g_m/I_D ⇒ 0.59%

CC ⇒ 0.55%

Both methods present similar behavior and almost the same relative standard deviation.

Example of application:

V_T variation vs. temperature



In this example, the *CC* method is used for tracking the V_T variation as a function of a specific parameter (temperature).

Conclusions

- A new procedure for the direct determination of the threshold voltage with minimum influence of second order effects is introduced
- 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.
- The current-based extraction in weak-moderate inversion allows the design of low power V_T-extractor circuits.