MODEL COMPACT PENTRU TRANZISTOARE MOS SUBMICRONICE PENTRU APLICATII ANALOGICE

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Cuprins

- *Evolutia tehnologiei CMOS*
- *Saturatia vitezei. Degradarea mobilitatii*
- *Model compact al tranzistorului MOS*
- *Comparatii model –date experimentale*
- *Concluzii*

Microelectronica

- Tranzistorul bipolar – începutul microelectronicii
- Descoperire importanta a sec. 20
- Dec. 1947 patent-tranz.cu contact punctiform-amplificator
- Sept. 1951, tranzistorul cu joncţiuni

The Revolution Begins

Invented 60 years ago, the transistor is a key building block of today's digital world. Perhaps the most important invention of the 20th century, transistors are found in many devices and are the building blocks of computer chips. Intel, the largest manufacturer of computer chips, continues to innovate to help PCs and laptops become smaller, faster, sleeker and more energy-efficient. Many new applications and inventions powered by transistors have impacted all of our lives over the past 60 years.

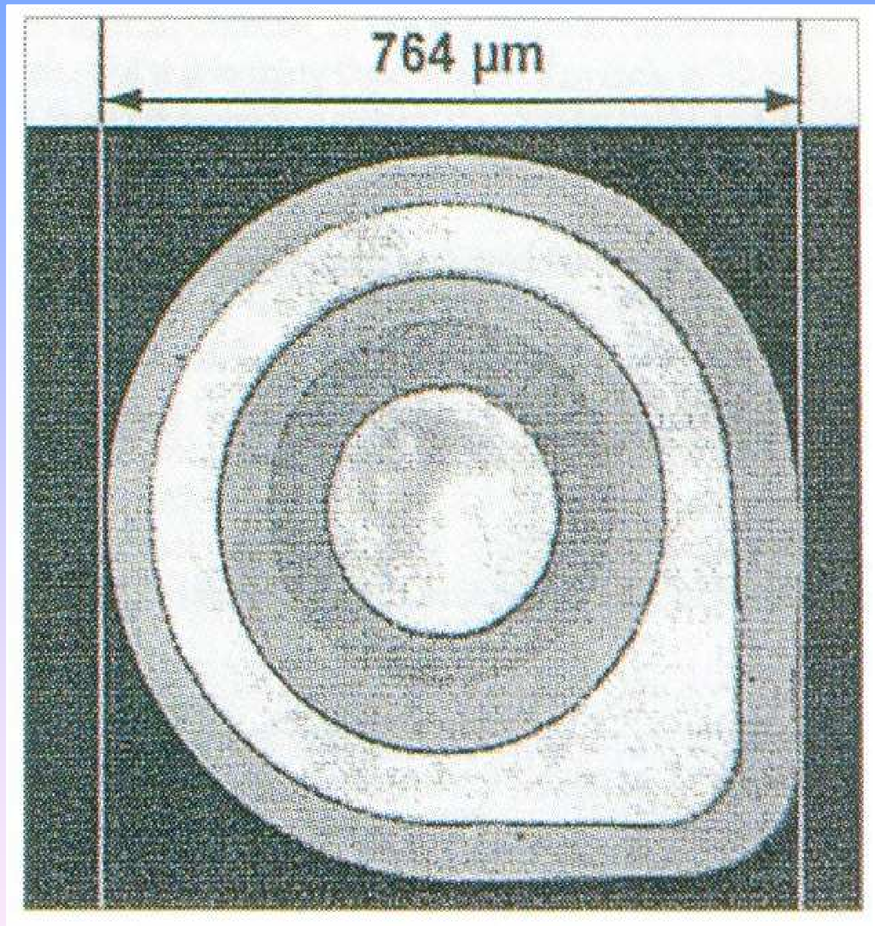
Circuite Integrate- aplicaţii

Impactul industriei semiconductoare este uriaş în multiple domenii:

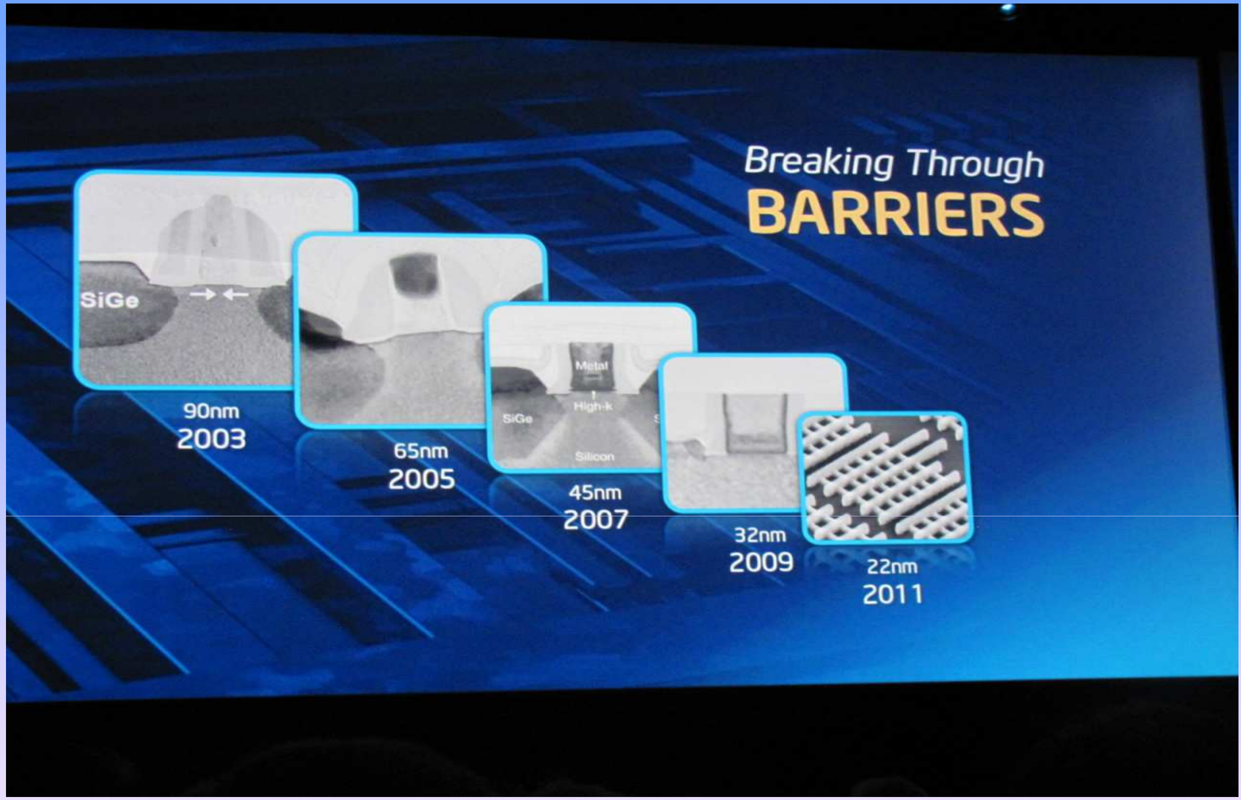
- PC/ laptopuri
- Carduri
- Comunicaţii / telefonie mobilă
- Multimedia(tv, jurnale electronice)
- Sisteme audio & video portabile
- Electronică medicală
- Electronică auto
- GPS – Global Positioning System
- Aplicaţii militare
- Explorarea spaţiului

Inceputul CI

- 1959- primul TB planar
  - Diametru -30 inch
  - Dimensiunea minimă-3 inch
- 1962 – primul CI
  - Produs de Fairchild
  - 4 tranzistoare + 6 rezistoare
  - 6 fire de conexiune
  - Încapsulat în TO5
- 1965- Micrologic circuit
  - Produs de Fairchild
  - 50 componente

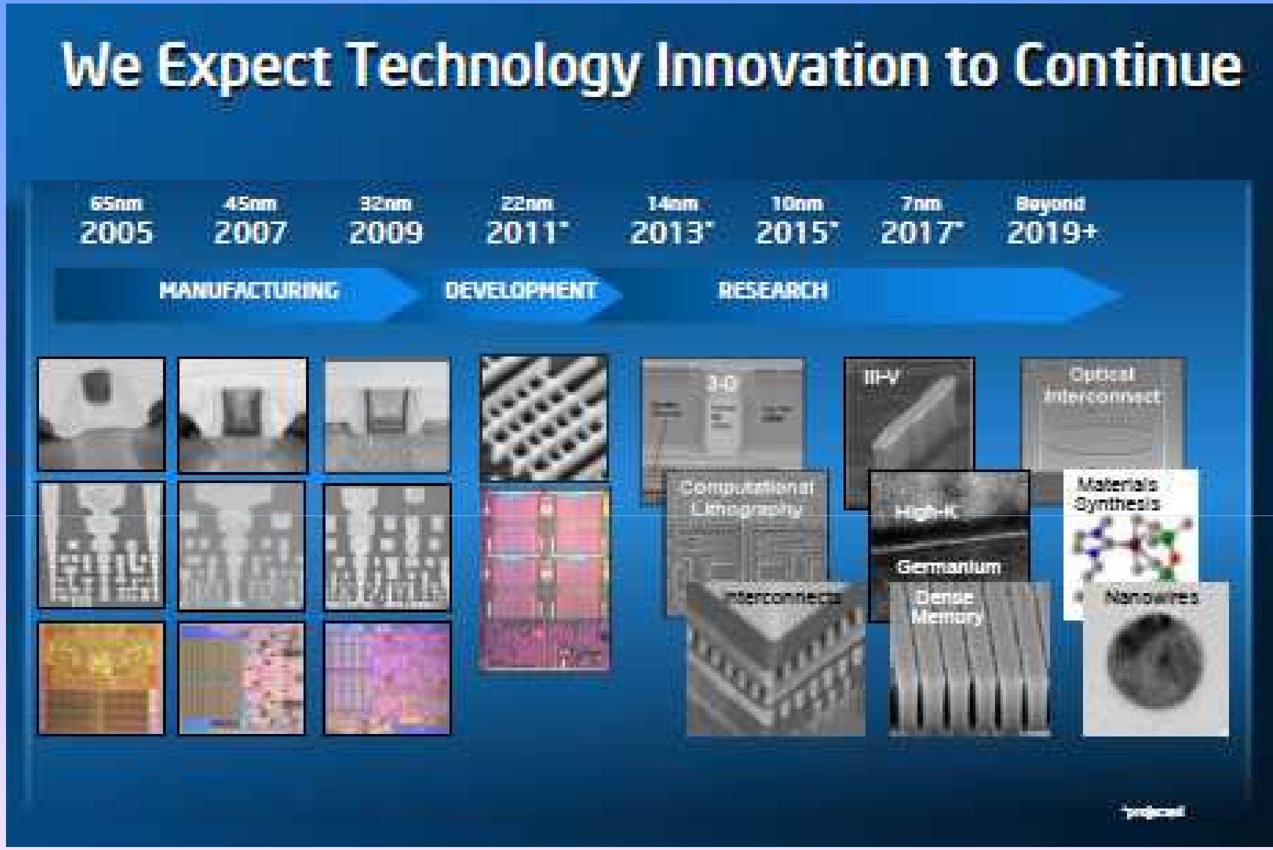


Scalarea lungimii canalului
Dimensiuni nanometrice



- Tehnologii CMOS
- 2 ani rata de innoire
- Circuite VLSI digitale

Scalarea lungimii canalului Previziuni



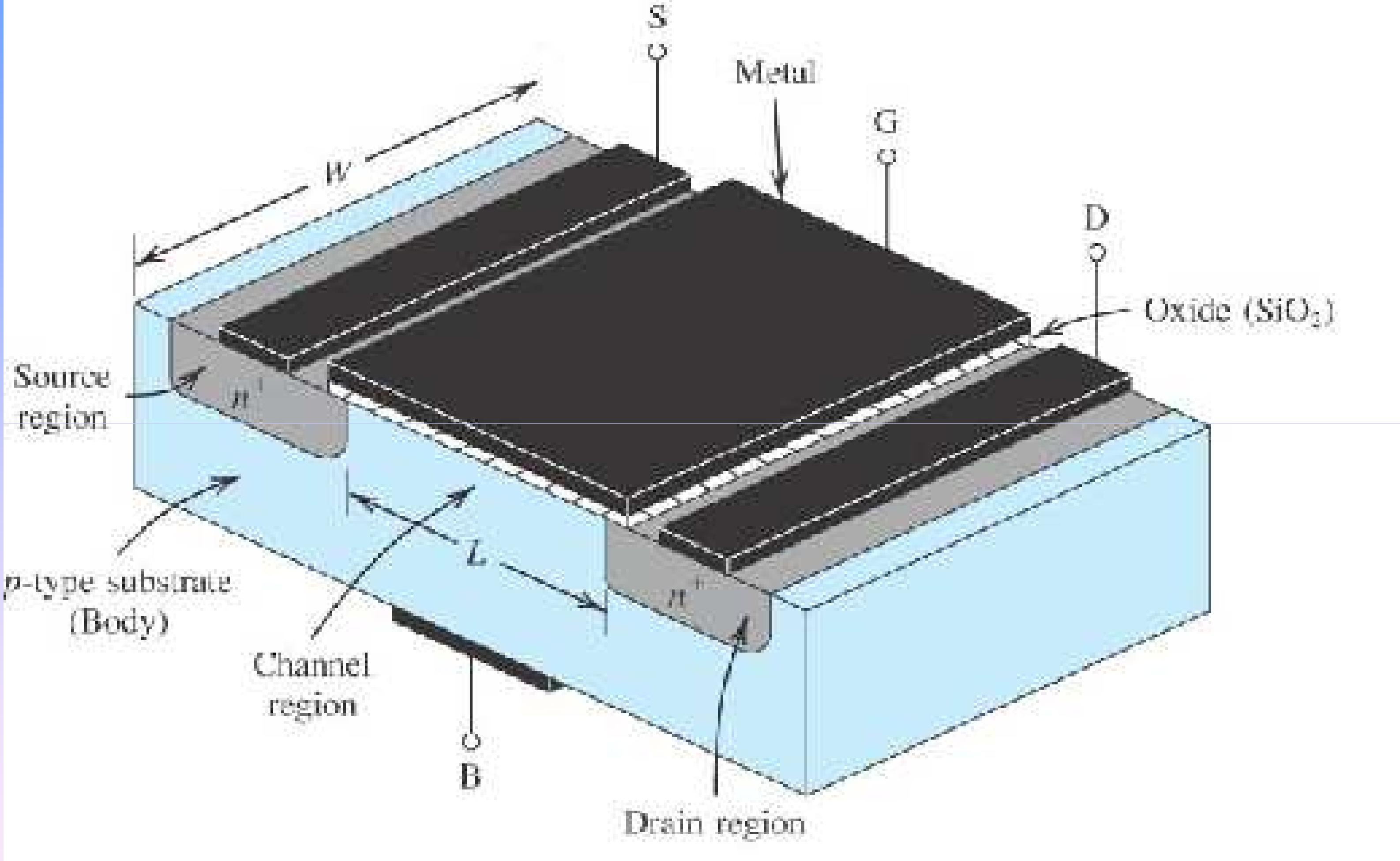
- Nanofire
- Conexiuni optice
- Litografie computationala

INTEL - Evolutia microprocesoarelor
Multi -cores

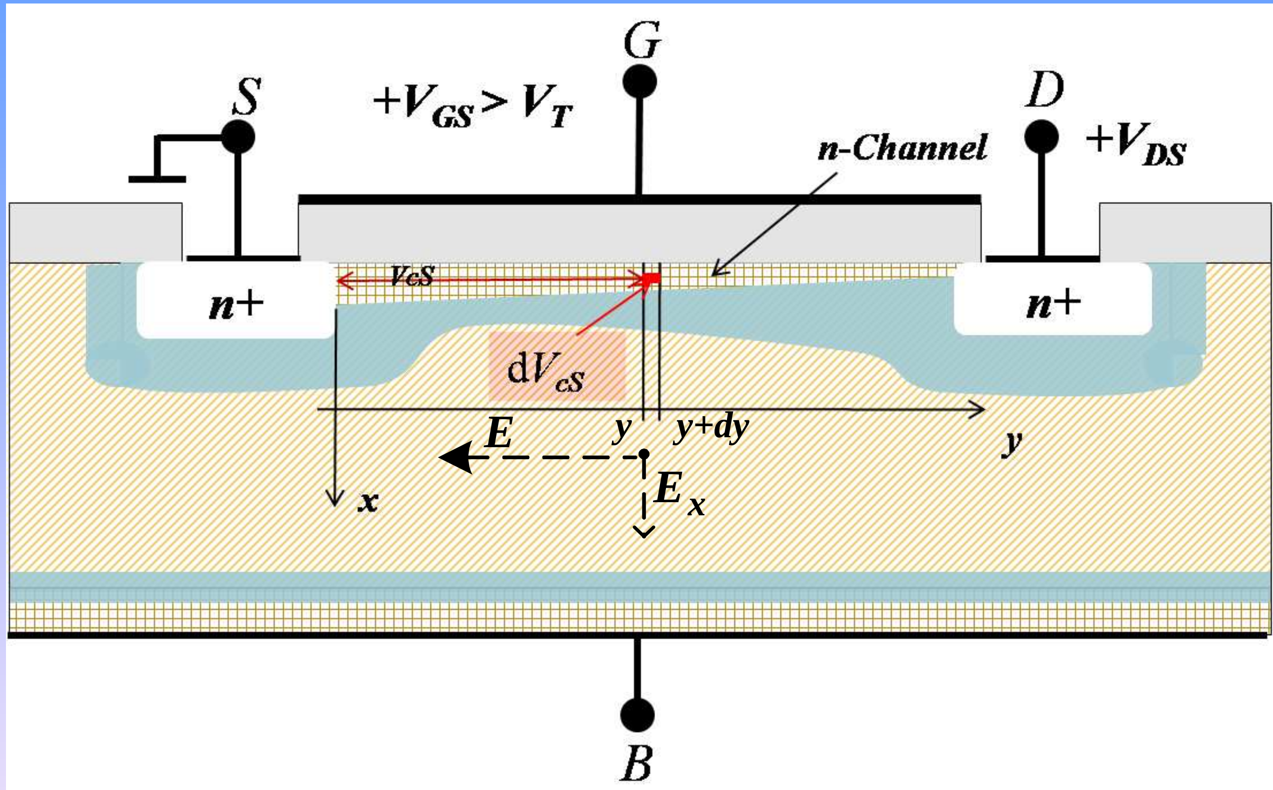
Microelectronica

- Preţul unui tranzistor din CI echivalează azi costul tipăririi unui caracter (literă) într-o publicaţie oarecare;
- Acum o memorie DRAM de *4MB* si *4milioane* de tranzistoare costă mai puţin decât un tranzistor în 1960;
- Nr. de caractere din toate tipăriturile depăşeşte cu doar un ordin de mărime nr. de tranzistoare incluse în CI fabricate până în prezent.

nMOS –Structura tridimensionala



nMOS –Efecte de canal scurt



- ❖ ξ_x- campul transversal - degradarea mobilitatii
- ❖ ξ - campul longitudinal – saturatia vitezei

Degradarea mobilitatii

$$\mu(y)=\frac{\mu_0}{1+\dfrac{\xi_x(y)}{\xi_{x,c}}}$$

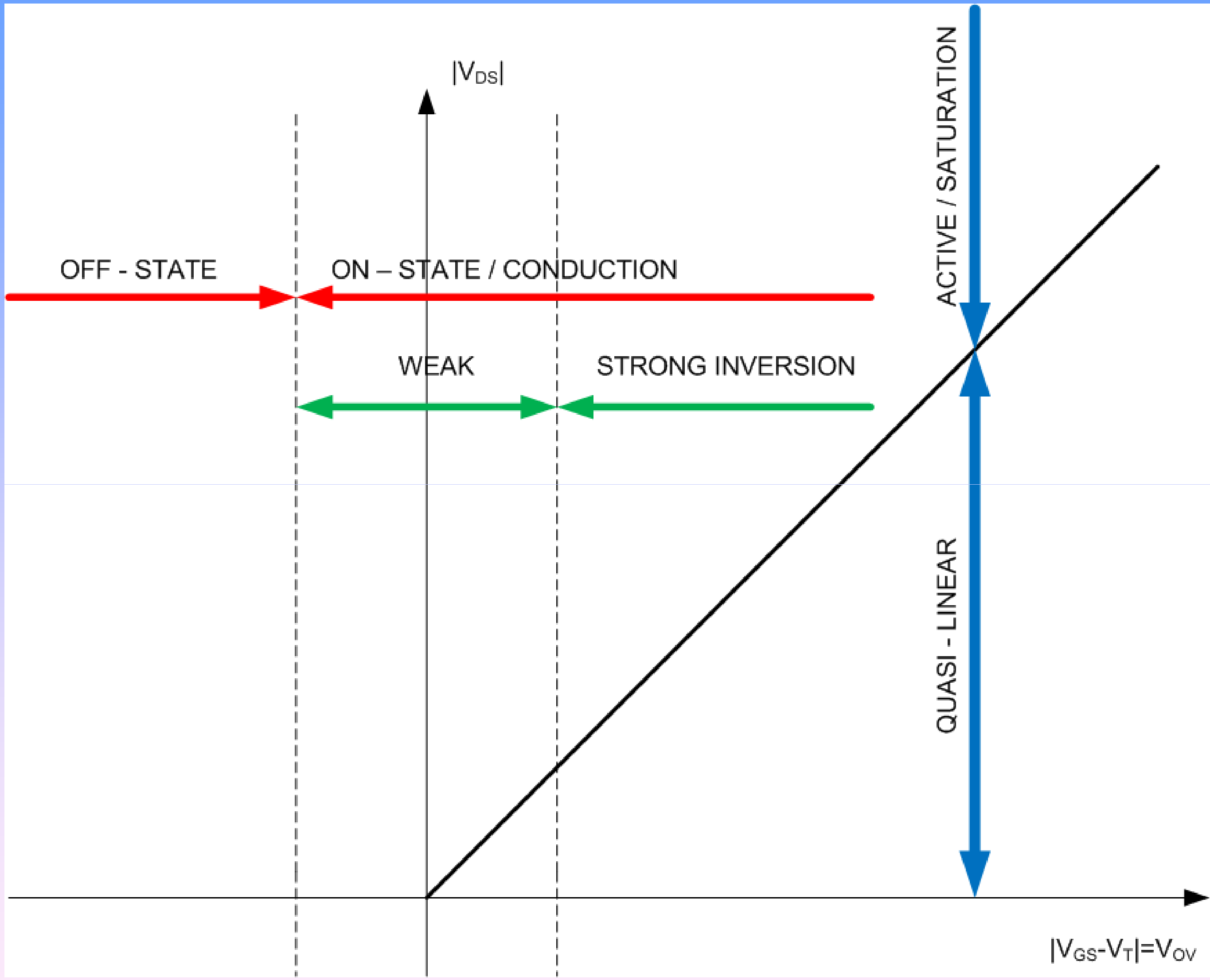
- $\xi_x(y)\cong\dfrac{V_{OV}+2V_T-V_{cS}(y)}{6t_{ox}}$ - campul electric transversal
- $\xi_{x,C}=1.5V/\mu m$ - campul transversal critic
- $V_{OV}=V_{GS}-V_T$ - tensiunea de comandă efectivă
- V_T - tensiunea de prag
- t_{ox} - grosimea oxidului de poartă

Saturatia vitezei

$$v(y) = \frac{\mu\,\xi(y)}{\left(1 + \left(\xi(y)/\xi_c\right)^{\alpha}\right)^{1/\alpha}}$$

- $v(y)$ - viteza purtatorilor mobili în canal
- $\xi(y) = \frac{V_{cS}}{L}$ - campul electric vertical/longitudinal
- $\xi_C = 1.5V/\mu m$ - campul (vertical)critic
- $\alpha = 1/\alpha = 2$ - pt. goluri(*p*- MOS)/electroni(*n* -MOS)

MOS – regiuni de funcţionare



Modelarea in inversie puternica(1)

$$I_D = Wv(y)\left|Q_I(y)\right|$$

$Q_I(y) = C_{ox}\left(V_{GS} - V_T - V_{cS}(y)\right)$ - Sarcina purtatorilor mobili din canal

C_{ox} - Capacitatea oxidului de poarta

$$I_D = W[C_{ox}(V_{GS} - V_T - V_{cS}(y))]\frac{\mu(y)\dfrac{dV_{cS}}{dy}}{\left[1+\left(\dfrac{dV_{cS}}{dy}\Big/\xi_c\right)^{\alpha}\right]^{1/\alpha}}$$

$$\int_0^L I_D\left[1+\left(\frac{dV_{cS}}{dy}\Big/\xi_c\right)^{\alpha}\right]^{1/\alpha} dy = WC_{ox}\mu_0\int_0^{V_{DS}}\frac{V_{OV} - V_{cS}(y)}{1+\dfrac{V_{OV}+2V_T - V_{cS}(y)}{V_{GS,C}}}dV_{cS}$$

Modelarea in inversie puternica (2)

$$I_D = \frac{W}{L}\cdot\mu_0 C_{ox}\cdot\frac{1}{1+\frac{V_{DS}}{V_{DS,C}}}\left[V_{GS,C}\cdot V_{DS} + V_{GS,C}\cdot\left(V_{GS,C}+2V_T\right)\cdot\ln\left(1-\frac{V_{DS}}{V_{OV}+2V_T+V_{GS,C}}\right)\right]$$

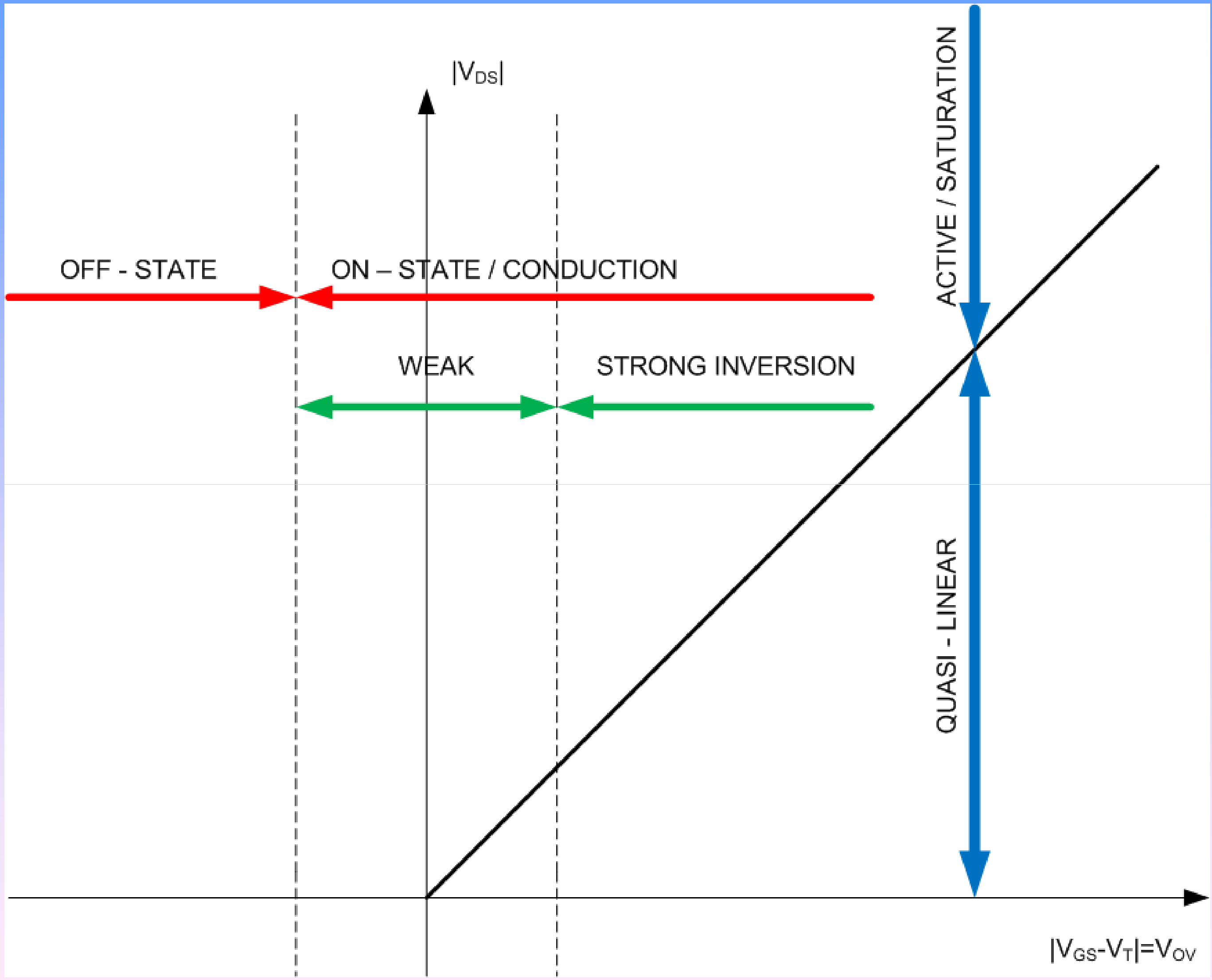
$V_{DS,C} = aL\xi_c$ - Tensiunea de drenă critică

$V_{GS,C} = 6\xi_{x,c}t_{ox}$ - Tensiunea de poarta critică

$$\ln\left(1+x\right)\cong x-\frac{x^2}{2} \quad pt. \quad x<<1$$

$$I_D \cong \frac{W}{L}\cdot\mu_0 C_{ox}\frac{1}{1+\frac{V_{OV}+2V_T}{V_{GS,C}}}\cdot\frac{1}{1+\frac{V_{DS}}{V_{DS,C}}}\left[V_{OV}\cdot V_{DS}-\frac{1}{2}\frac{V_{DS}^2}{1+\frac{V_{OV}}{2V_T+V_{GS.C}}}\right]$$

MOS – regiuni de funcţionare



Curentul de drena in zona de trioda

Modelul nou

$$I_D \cong \frac{W}{L} \cdot \mu_{eff} C_{ox} \cdot \frac{1}{1+\frac{V_{DS}}{V_{DS,C}}} \left[V_{OV} \cdot \left(1+\overline{V_{OV}}\right) \cdot V_{DS} - \frac{1}{2} \cdot V_{DS}^2 \right]$$

$$\mu_{eff} = \frac{\mu_0}{1+\frac{2V_T}{V_{GS,C}}} \cdot \frac{1}{\left(1+\overline{V_{OV}}\right)^2}$$ - Mobilitatea efectivă la campuri longitudinale mici

$$\overline{V_{OV}} = \frac{V_{OV}}{2V_T + V_{GS,C}}$$ - Tensiunea de comanda efectiva normata

Modelul clasic

$$V_{OV} = V_{GS} - V_T << V_{GS,C}$$ - Efectul campului transversal-neglijabil

$$V_{DS} << V_{DS,C}$$ - Efectul campului longitudinal-neglijabil

$$I_D \cong \frac{W}{L} \cdot \mu_0 C_{ox} \left[V_{OV} \cdot V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

Curentul de drena in zona activa (1)

❖ Modelul nou

$$I_D = \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_{eff} C_{ox} . V_{DS,act}^2 = I_{D,C} \frac{V_{DS,act}^2}{V_{DS,C}^2}$$

$$V_{DS,act} = V_{DS,C} \left(\sqrt{1 + 2 \frac{V_{OV}}{V_{DS,C}} \cdot \left(1 + \overline{V_{OV}}\right)} - 1 \right)$$ - tensiunea de drena la limita intre zona de trioda si zona activa

$$I_{D,C} = \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_{eff} C_{ox} . V_{DS,C}^2$$ - curentul de drena critic

❖ Modelul clasic $\left(V_{OV} = V_{GS} - V_T << V_{GS,C} \quad V_{DS} << V_{DS,C} \right)$

$$V_{DS,act} = V_{DS,sat} = V_{OV} = V_{GS} - V_T$$

$$I_D \cong \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_0 C_{ox} \cdot V_{DS,act}^2 = \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_0 C_{ox} \cdot V_{DS,OV}^2$$

Curentul de drena in zona activa (2)
Cazuri limită

$$I_D = \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_{eff} C_{ox} . V_{DS,act}^2 = I_{D,C} \frac{V_{DS,act}^2}{V_{DS,C}^2}$$

❖ Tensiune de comandă mică $\left(V_{OV} << V_{GS,C} \quad V_{OV} << V_{DS,C} \right)$

$$V_{DS,act} \cong V_{OV} \qquad I_D = \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_0 C_{ox} . V_{OV}^2$$

❖ Tensiune de comandă medie

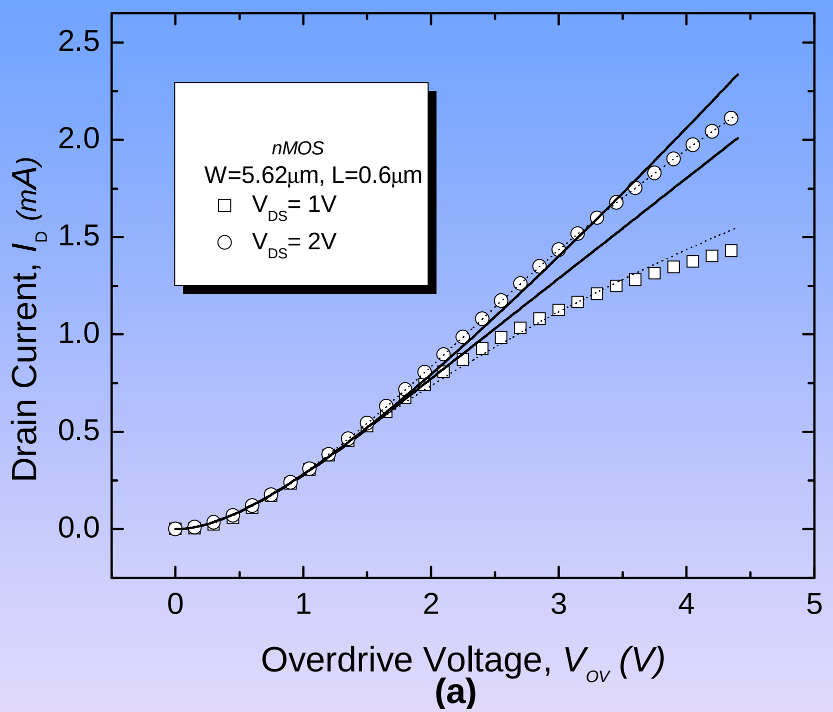
$$V_{DS,act} = V_{DS,C} \qquad I_D = I_{D,C} = \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_{eff} C_{ox} . V_{DS,C}^2$$

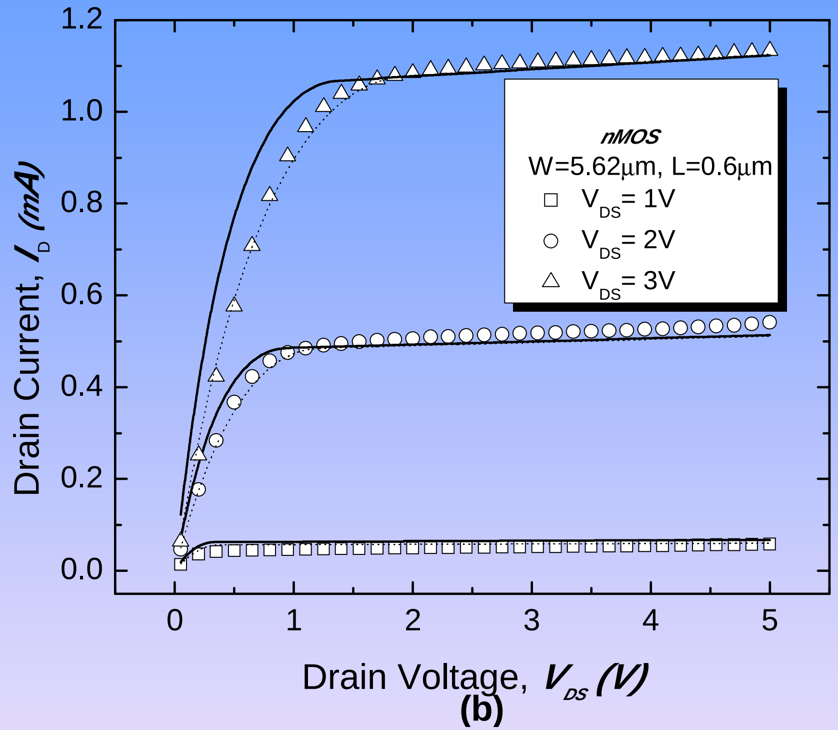
❖ Tensiune de comandă mare $V_{OV} >> V_{DS,C}$

$$V_{DS,act} \cong \sqrt{2 V_{OV} V_{DS,C} \left(1 + \overline{V_{OV}} \right)}$$

$$I_D \cong \frac{1}{2} \cdot \frac{W}{L} \cdot \mu_0 C_{ox} \cdot V_{GS,C} \cdot V_{DS,C} = const.$$

nMOS - comparatie model - experiment





Caracteristici de transfer

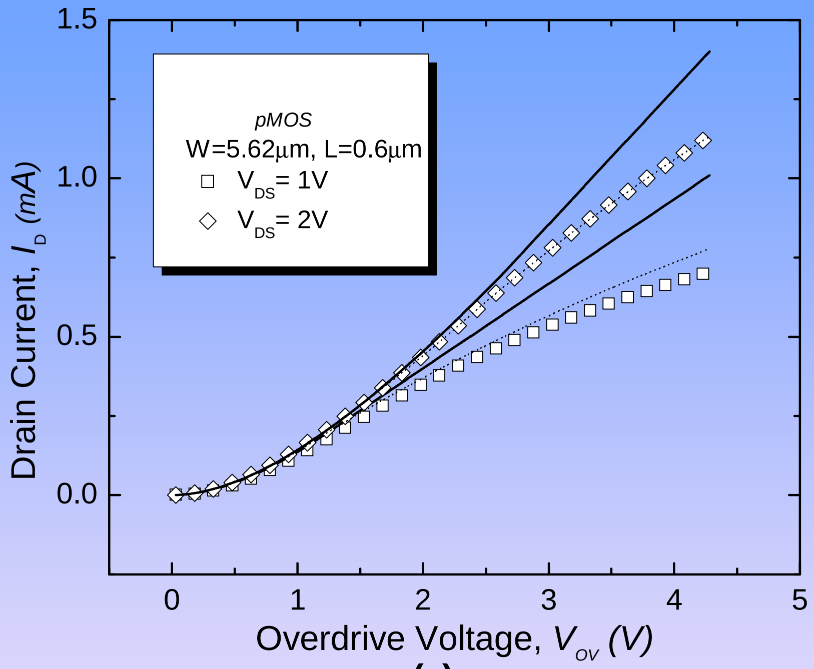
Caracteristici de iesire

Date experimentale - simboluri

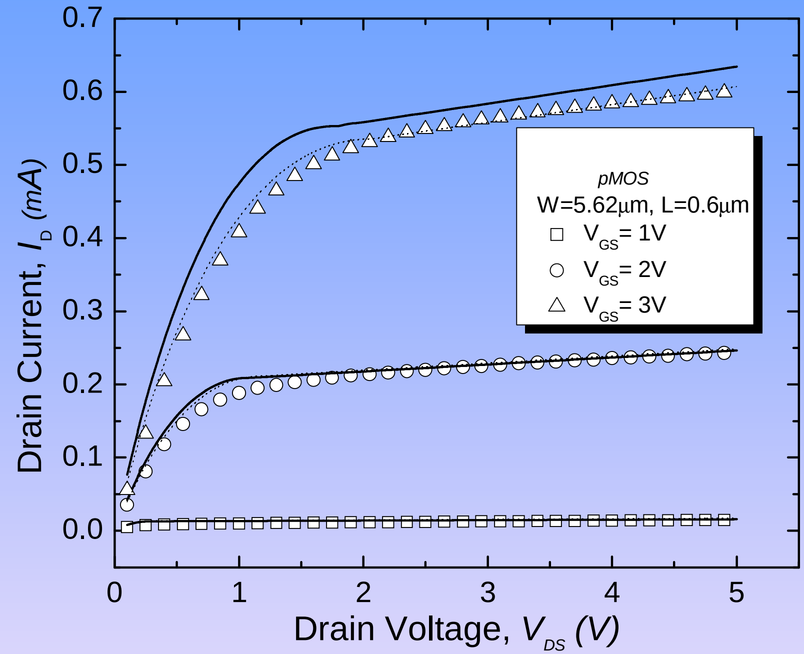
Model complet - linie intrerupta

Model simplu(fara degradarea mobilitatii) - linie continua

pMOS - comparatie model - experiment



(a)



(b)

Caracteristici de transfer

Caracteristici de iesire

Date experimentale - simboluri

Model complet - linie intrerupta

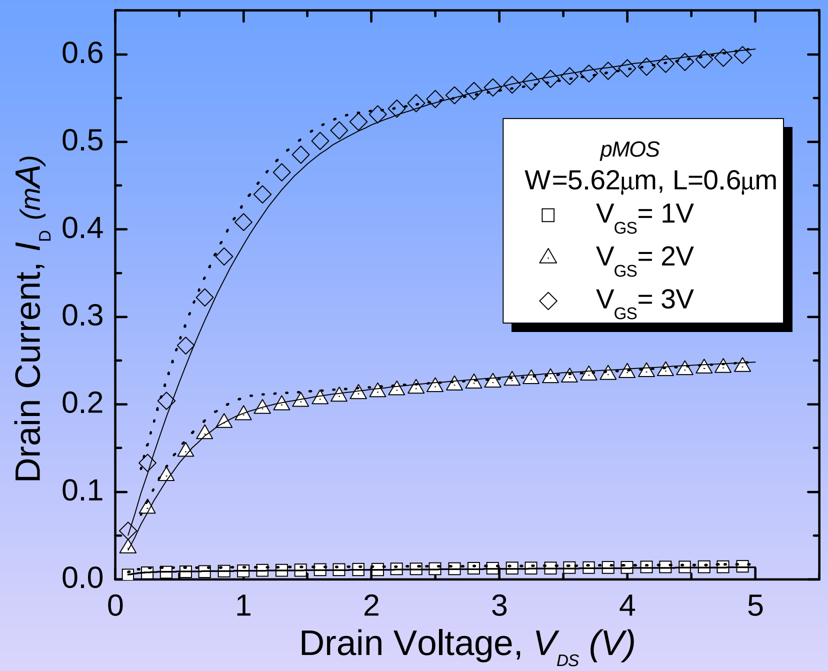
Model simplu(fara degradarea mobilitatii) - linie continua

Comparatie model – experiment

Characteristic	Device	W/L	Model error (%)	
			Simplu	Complet
ID – VDS VGS = 3V	nMOS	0.7/0.6	5.68	0.35
	nMOS	5.62/0.6	4.95	0.08
	pMOS	5.62/0.6	8.22	2.35
ID – VGS VDS = 2V	nMOS	0.7/0.6	2.37	0.36
	nMOS	5.62/0.6	1.7	1.7
	pMOS	5.62/0.6	5.01	0.72

- Se observa micsorarea erorii pentru modelul complet
- Motivul este combinarea efectelor de canal scurt

Comparatie model – experiment - BSIM



(c)

Date experimentale - simboluri

Model complet - linie intrerupta

BSIM - linie continua

Transconductanta - panta tranzistorului

$$g_m = \frac{i_d}{v_{gs}} = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{I_D, V_{DS}}$$

Parametru dinamic-defineste performantele de amplificare

❖dependenta de curent

$$g_m = g_{m,c} \frac{1}{1+\sqrt{I_{D,C}/I_D}} \left(1+\sqrt{\frac{I_D}{I_{D,C}}}\,\frac{V_{DS,C}}{2V_T + V_{GS,C}}\right)$$

$$g_{m,c} = \frac{W}{L} \cdot \mu_{eff} C_{ox} . V_{DS,C}$$

❖ dependenta de tensiunea de comanda efectiva

$$g_m = g_{m,c}\left(1-\frac{1}{\sqrt{1+2\frac{V_{OV}}{V_{DS,C}}\cdot\left(1+\sqrt{V_{OV}}\right)}}\right)\left(1+\frac{2\sqrt{V_{OV}}}{\sqrt{1+2\frac{V_{OV}}{V_{DS,C}}\cdot\left(1+\sqrt{V_{OV}}\right)}+1}\right)$$

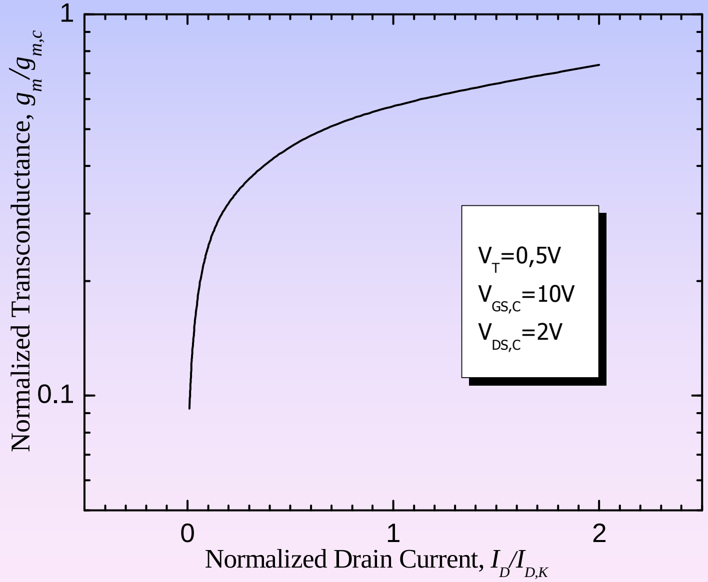
Transconductanta - cazuri limita

- Curenti mici - saturatia vitezei neglijabilă $I_D << I_{D,C}$

$$g_m \cong g_{m,c}\sqrt{\frac{I_D}{I_{D,C}}} = \sqrt{2\frac{W}{L}\mu_{eff}C_{ox}I_D}$$

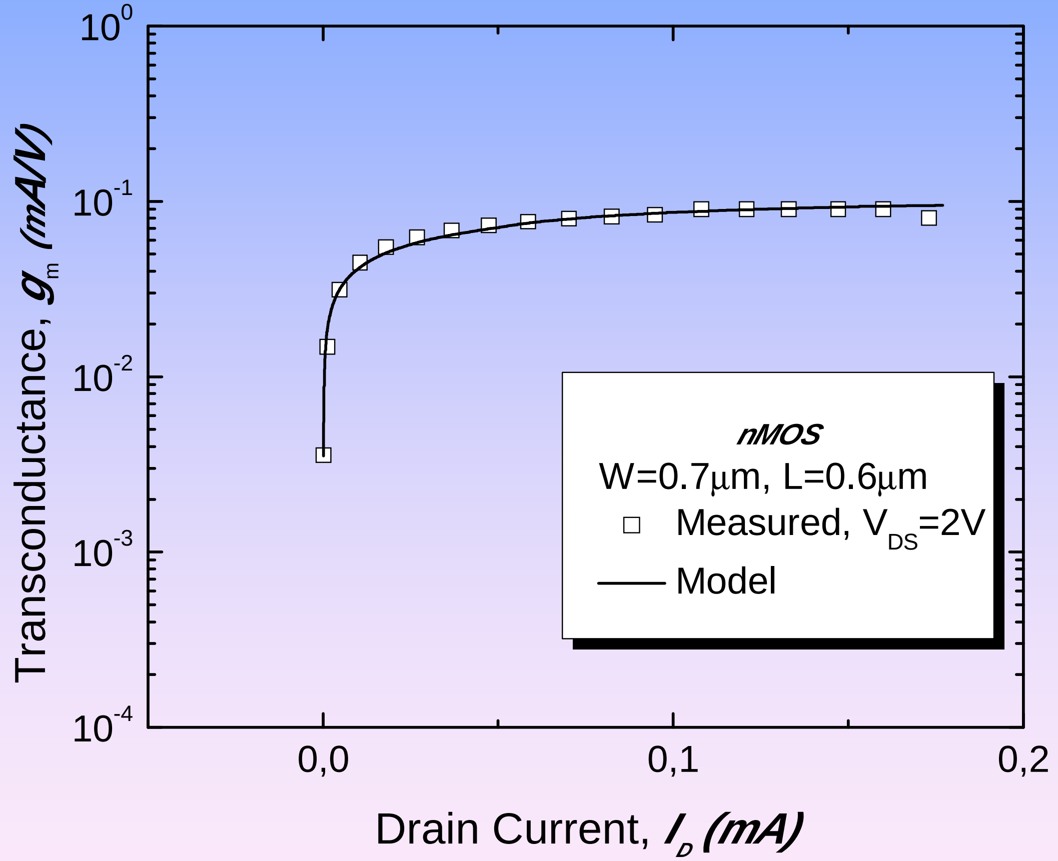
- Curenti mari $I_D >> I_{D,C}$

$$g_m \to g_{m,c} = \frac{W}{L}\cdot\mu_{eff}C_{ox}.V_{DS,C} = W\cdot\mu_{eff}C_{ox}.\xi_C$$



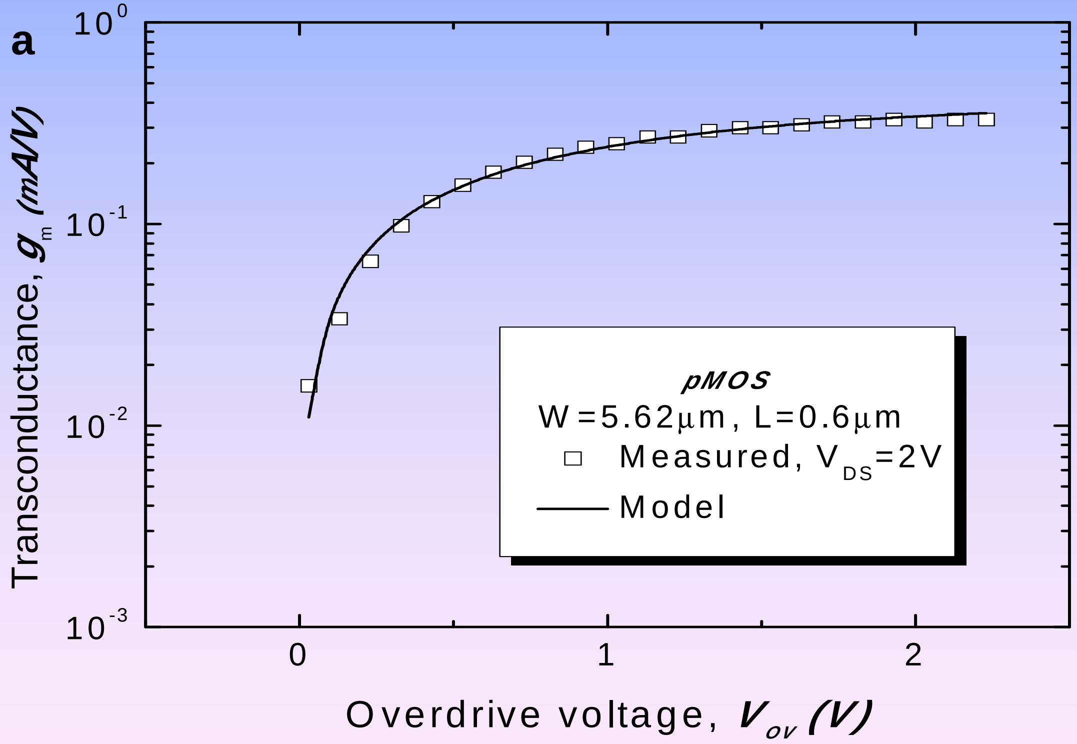
Transconductanța- dependenta de curent

$$g_m = g_{m,c}\frac{1}{1+\sqrt{I_{D,C}/I_D}}\left(1+\sqrt{\frac{I_D}{I_{D,C}}}\frac{V_{DS,C}}{2V_T+V_{GS,C}}\right)$$



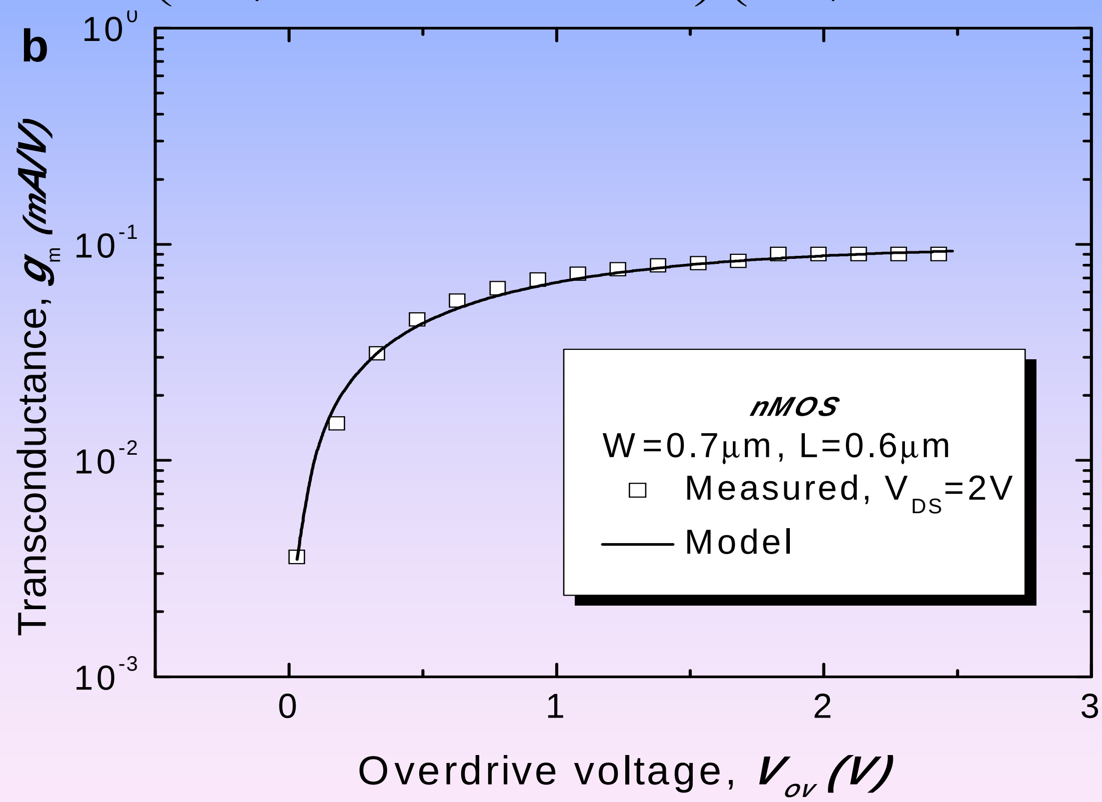
pMOS-Transconductanța- dependenta de V_{OV}

$$g_m = g_{m,c}\left(1-\frac{1}{\sqrt{1+2\frac{V_{OV}}{V_{DS,C}}\cdot\left(1+\sqrt{V_{OV}}\right)}}\right)\left(1+\frac{2\sqrt{V_{OV}}}{\sqrt{1+2\frac{V_{OV}}{V_{DS,C}}\cdot\left(1+\sqrt{V_{OV}}\right)}+1}\right)$$



nMOS-Transconductanța- dependenta de V_{OV}

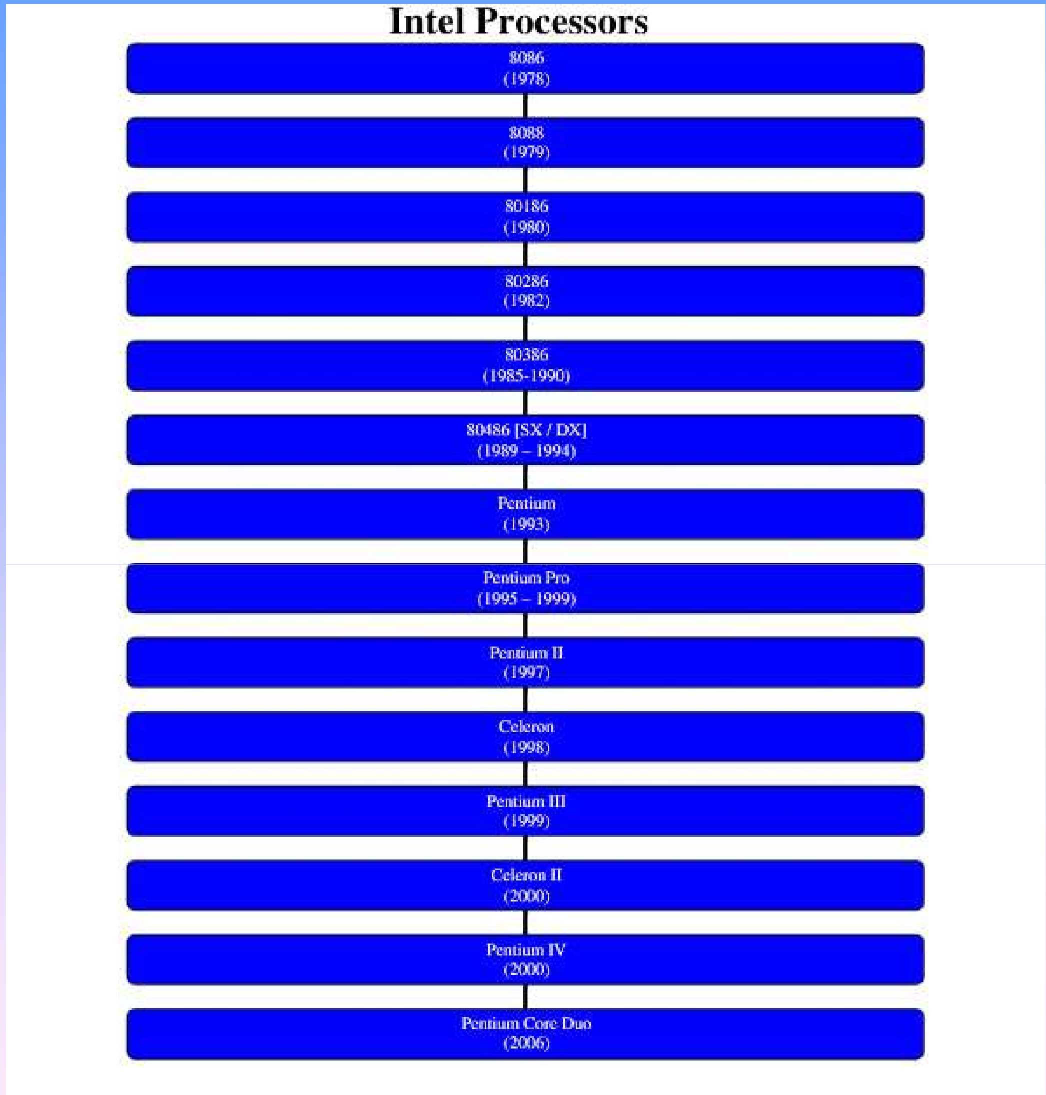
$$g_m = g_{m,c}\left(1-\frac{1}{\sqrt{1+2\frac{V_{OV}}{V_{DS,C}}\cdot\left(1+\overline{V_{OV}}\right)}}\right)\left(1+\frac{2\overline{V_{OV}}}{\sqrt{1+2\frac{V_{OV}}{V_{DS,C}}\cdot\left(1+\overline{V_{OV}}\right)}+1}\right)$$



Concluzii

- Tehnologiile CMOS evolueaza spre dimensiuni nano
- Campul electric in canal devine semnificativ
- Campul transvesal $\Rightarrow$ degradarea mobilitatii
- Campul longitudinal $\Rightarrow$ saturaţia vitezei
- Model compact – model analitic ce include pentru prima oara efectul combinat al degradarii mobilitatii si saturatiei vitezei
- Ecuatii pentru I_D *si* g_m similare cu cele ale modelului clasic
- Modelul este validat prin comparatii cu date experimentale masurate pe *n* MOS si *p* MOS fabricate in tehn.CMOS de 0,22um
- Rezultate apropiate de BSIM3-model folosit in simulatoare
- Poate fi usor implementat in simulatoare
- Articol acceptat - **International Journal of Electronics**

INTEL - Evolutia microprocesoarelor



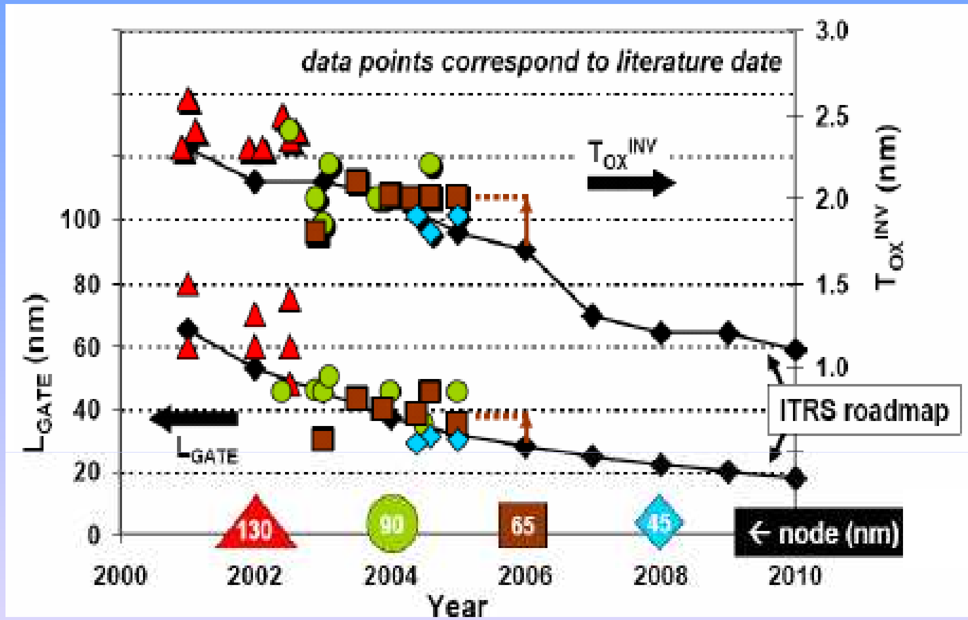
1971 - primul microprocesor

1978 - 8086

1993 – Pentium

2006 – Pentium dual core

Scalarea lungimii canalului si grosimii oxidului de poarta



SiO_2 - T_{ox} a scazut pana 1,2 nm (5 distante atomice):

- curenti de poarta foarte mari,
- neuniformitate accentuata pe o placheta de 12 inch
- randamentul si fiabilitatea scad dramatic
- Dielectrici high *k*