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A FUNDAMENTAL PROPERTY OF MOS TRANSISTORS

(AND ITS CIRCUIT IMPLICATIONS)

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INTRODUCTION

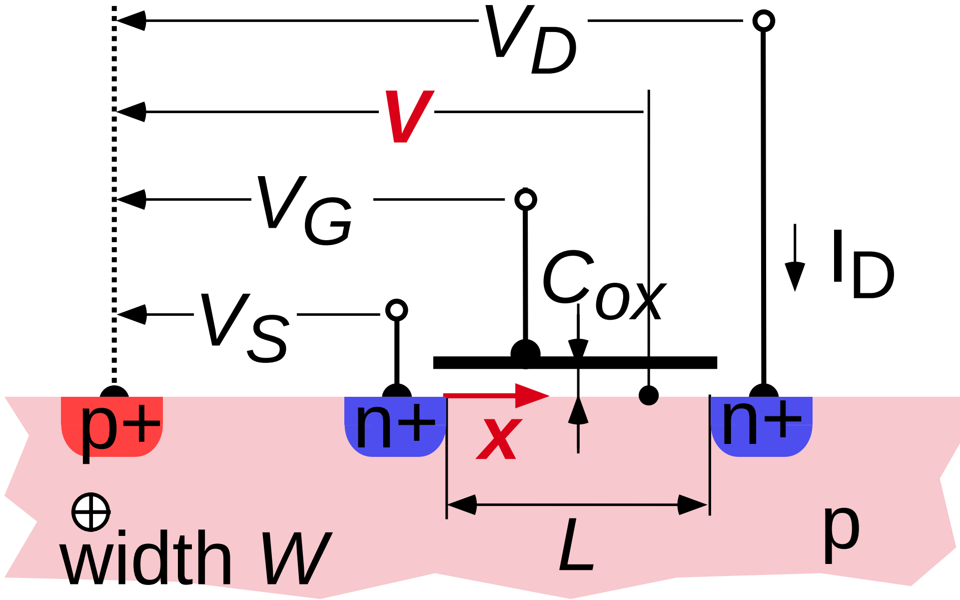
- Goals of compact transistor modeling:
  - simulation by quantitative calculation on computer
  - highlighting properties to facilitate
    - understanding circuits
    - synthesis of robust circuits

- Best models: combine both goals by hierarchical structure
  example: EKV model.

- EKV approach will be used to introduce and discuss a fundamental property. [1]

DEFINITIONS

for EKV model [2,3]



- Substrate referred-voltages

  V_S, V_D, V_G

- Position x along the channel
- Local "channel voltage" V

  splitting of quasi-Fermi levels due non-0 V_S and/or V_D

  $V = V_S$ at source

  $V = V_D$ at drain

  n-channel: holes at equilibrium

  thus V = electron quasi-Fermi level + constant.

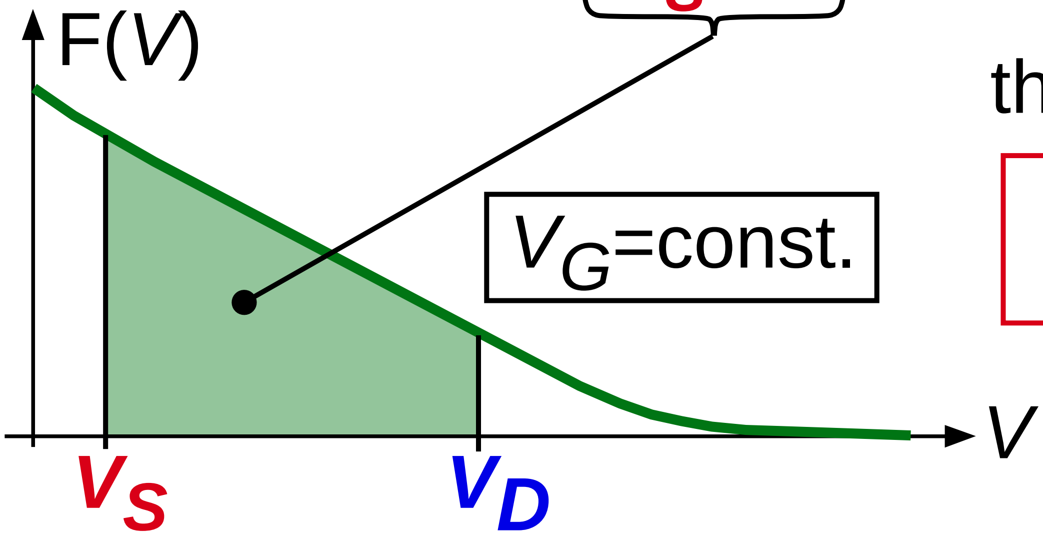
FUNDAMENTAL PROPERTY (1)

- For a long and wide channel:

$$I_D = \mu W(-Q_i)\,\frac{dV}{dx} = \frac{\mathbf{F}(V,V_G)\,dV}{\mathbf{G}(x,V_G)\,dx}$$

- Condition: separable in V and x

$$\text{then: } I_D\int_0^L \mathbf{G}\,dx = \int_{V_S}^{V_D} \mathbf{F}\,dV \equiv \int_{V_S}^{\infty} \mathbf{F}\,dV - \int_{V_D}^{\infty} \mathbf{F}\,dV$$



thus:

$$I_D = \mathbf{I}(V_S,V_G) - \mathbf{I}(V_D,V_G)$$

FUNDAMENTAL PROPERTY (2)

$$I_D = \mathbf{I}(V_S, V_G) - \mathbf{I}(V_D, V_G)$$

- The drain current is the superposition of independent and symmetrical effects of source and drain voltages.

- Definitions:
  - **Forward** current $I_F = \mathbf{I}(V_S, V_G)$, independent of V_D
  - **Reverse** current $I_R = \mathbf{I}(V_D, V_G)$, independent of V_S

then $I_D = I_F - I_R$

DOMAIN OF VALIDITY (1)

- Condition:

$$\mu W(-Q_i) = \frac{\mathbf{F}(V, V_G)}{\mathbf{G}(x, V_G)}$$

with: $-Q_i = C_{ox}(V_G - V_{FB} - \Psi_s) - \sqrt{2qN_b\varepsilon_{si}\Psi_s}$

total charge — depletion charge Q_b

- Mobile charge Q_i depends on surface potential Ψ_s, and $\Psi_s = f(V)$, thus Q_i should not be a (direct) function of x to be part of **F**. Therefore:

  - V_G-V_{FB}
  - C_{ox}
  - N_b

  - must be independent of position x along the channel : homogeneous channel.
  - but may depend on Ψ_s or V (or z for N_b) (*e.g.*: $C_{ox}(\Psi_s)$: polydepletion)

DOMAIN OF VALIDITY (2)

- Condition: $$\mu W(-Q_i) = \frac{\mathbf{F}(V, V_G)}{\mathbf{G}(x, V_G)}$$

- *W* is independent of *V;* thus:
  - part of **G**, may depend on *x*: ⇒ any shape of channel.

- Mobility μ depends on vertical field thus on Ψ_S , thus
  - included in **F**, provided velocity $v \ll v_{sat}$

    (otherwise depends on I_D itself)

- Furthermore, the effective value of *L* along which $\mathbf{G}(x, V_G)$ is integrated must be independent of I_D, V_S and V_D.

EFFECT OF NARROW CHANNEL

- Increased importance of side effects.
- Equivalent to parallel connection of several transistors with different characteristics.
    - if each transistor *i* fulfils

$$I_{Di} = \mathbf{I}_i(V_S, V_G) - \mathbf{I}_i(V_D, V_G)$$

    - then the sum I_D of I_{Di} fulfils it as well.
- The property is not degraded.

DOMAIN OF VALIDITY (SUMMARY)

The fundamental property is available

- For long and homogeneous channel
- Independently of channel shape
- Independently of $N_b(z)$
- Even if the channel is very narrow
- Even for large gate voltages reducing the mobility
- Even with polydepletion.

CAUSES OF DEGRADATION (1)

- Non homogeneous channel: Q_i direct function of x.

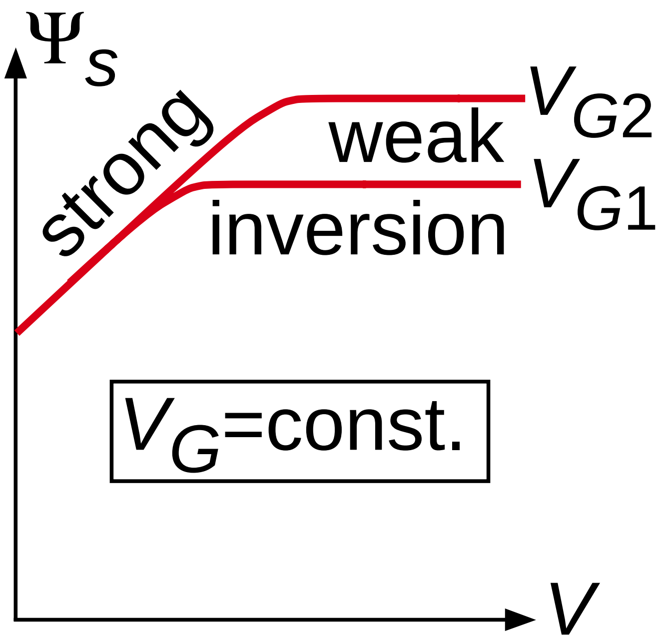
$$Q_i = -C_{ox}(V_G - V_{FB} - \Psi_s) + \sqrt{2q\, N_b\, \varepsilon_{si} \Psi_s}$$

There may be variations with position x in the channel...

- of substrate doping N_b, which can be
  - intentional (e.g.: LDD)
  - artifact of process (gradient or piling-up)
    (always present at very ends of channel)
- of flat-band voltage V_{FB} , caused by
  - variation of N_b
  - variation of charge in oxide
- of effective C_{ox}, always present at very ends of channel.

SPECIAL CASE OF WEAK INVERSION

- Weak inversion characterized by $Q_i \ll Q_b$, therefore:
  - Q_i has negligible effect on potential and field
- Can be expressed as $-Q_i = \mathbf{G}_q(\Psi_s)e^{-V/U_T}$
  - with Ψ_s independent of V, thus:
  - $\mathbf{G}_q$ can be any function of x and is included in **G**, therefore:
- The property is valid even if the channel is not homogeneous.



- Mobility μ independent of V(small vert. field), thus part of **G**, **F** is reduced to $\mathbf{F} = e^{-V/U_T}$: independent of V_G.

CAUSES OF DEGRADATION (2)

- Channel long ⇒ non-long ⇒ short
  - property progressively degraded by...
  - several independent mechanisms:

a. Voltage effects:

- channel length modulation
  - I_F or I_R becomes function of both V_D and V_S
  - effect proportional to $1/L$
- barrier lowering and 2-D effects: further degradation.

b. Current effects:

- if I_D is increased by reducing L, then
  ⇒ carrier velocity increases towards saturation
  ⇒ mobility reduced, thus function of I_D

c. Non-homogeneous channel (except in weak inversion):

- importance of end-effects proportional to $1/\boldsymbol{L}$.

CONCEPT OF PSEUDO-RESISTOR [4,5,6]

- We have shown that: $$I_D = \frac{1}{\int_0^L \mathbf{G}\,\mathrm{d}x}\left[\int_{V_S}^{\infty}\mathbf{F}\,\mathrm{d}V - \int_{V_D}^{\infty}\mathbf{F}\,\mathrm{d}V\right]$$

- Definitions:
  - pseudo-voltage: $$V^* = -K_0\int_V^{\infty}\mathbf{F}(V,V_G)\,\mathrm{d}V$$
  - pseudo-resistor: $$R^* = K_0\int_0^L \mathbf{G}\,(x,V_G)\,\mathrm{d}x$$

(where K_0: any positive constant)

- Results in pseudo Ohm's Law: $$I_D = (V_D^* - V_S^*)/R^*$$

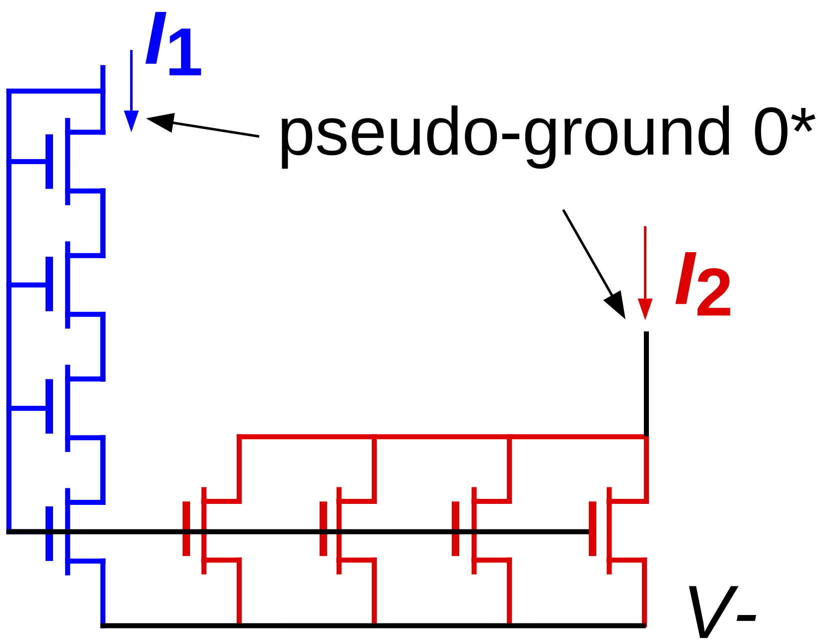
LINEAR CURRENT-MODE CIRCUITS

- Implications of pseudo Ohm's law $I_D = (V_D^* - V_S^*)/R^*$
  - Any network interconnecting transistors with same **F**(V,V_G) and same V_G is linear with respect to currents.
  - Any circuit of linear resistors can be implemented by transistors only, provided only currents are considered.
  - A resistor connected to ground (V=0) in the resistive prototype corresponds to a saturated transistor that provides a pseudo-ground (V^*=0).
- In weak inversion:
  - **F** indep. of V_G, but V_G included in function **G**, hence:
  - Different V_G possible for each transistor
  - Each R^* can be separately adjusted by its V_G.

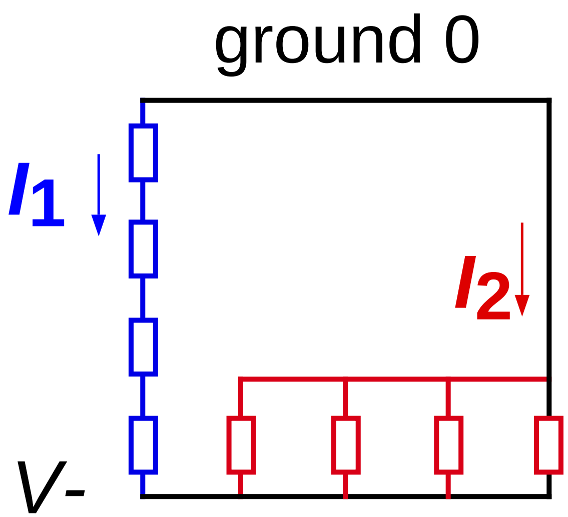
EXAMPLE OF APPLICATION OF PSEUDO-R

- Large-ratio current mirror
  - Use series/parallel combination of...
  - identical transistors, all in same substrate

  - transistor circuit:
  - pseudo-resistor prototype:

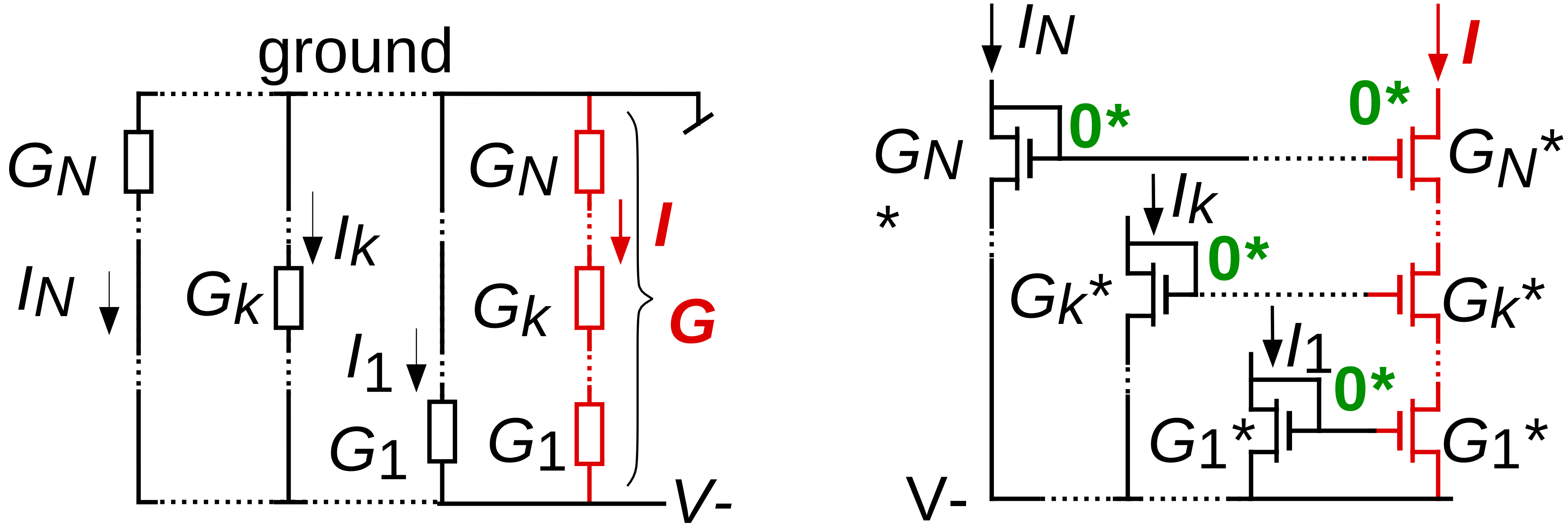


$I_2/I_1 = 16$



EXAMPLE OF APPLICATION IN WEAK INVERSION

- Calculation of harmonic mean [7]



resistive prototype

pseudo-resistive version (0*=pseudo-ground)

- Series combination of G_i: $\boldsymbol{G} = \dfrac{1}{\Sigma 1/G_i}$ **harmonic mean**

- Same voltage across $\boldsymbol{G}$ and G_i, thus $\boldsymbol{I} = \dfrac{1}{\Sigma 1/I_i} = \dfrac{I_{hm}}{N}$

APPLICATIONS OF PSEUDO-RESISTORS

- Simplification of circuit analysis
- Linear attenuators **[4]**(electrical control in weak inversion)
  - R-2R network for D/A conversion **[8]**.
- Spatial information processing:
  - n^{th} oder moment computation **[9,6,10,11]**
  - diffusion networks (isotropic or not) **[12,6]**
  - 2-D emulation of physical media **[13,6]**.
- In weak inversion: exploitation of current distribution in voltage- (or current-) dependent linear networks:
  - local normalisation in vision processing **[14,6]**
  - generation of nonlinear functions **[6, 15]**
  - energy minimizers.....

CONCLUSION

- MOS property for long and homogeneous channels:

$$I_D = \mathbf{I}(V_S, V_G) - \mathbf{I}(V_D, V_G) = I_F - I_R$$

  - superposition of independent and symmetrical effects of S and D voltages.
  - forward and reverse components.

- Property progressively degraded when channel shortened.

- Underlies the concept of pseudoresistor:
  - linear current mode circuits
  - transistor implementation of arrays of resistors.
  - simpler analysis of transistor circuits.

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