2008

Analytical modelling and performance analysis of Double-Gate MOSFET-based circuit including ballistic/quasi-ballistic effects

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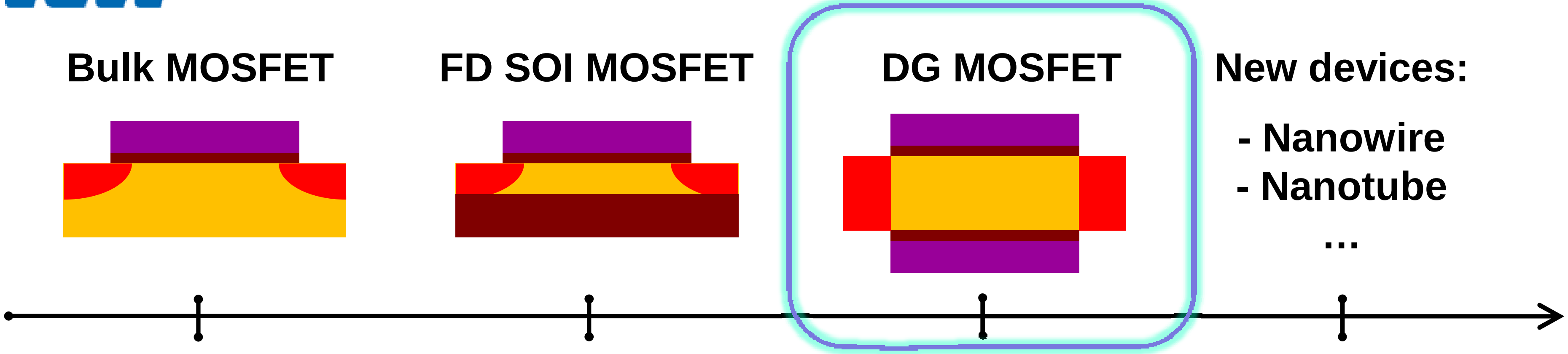
Context



Bulk MOSFET

FD SOI MOSFET

DG MOSFET

New devices:

- **Nanowire**
- **Nanotube**

…

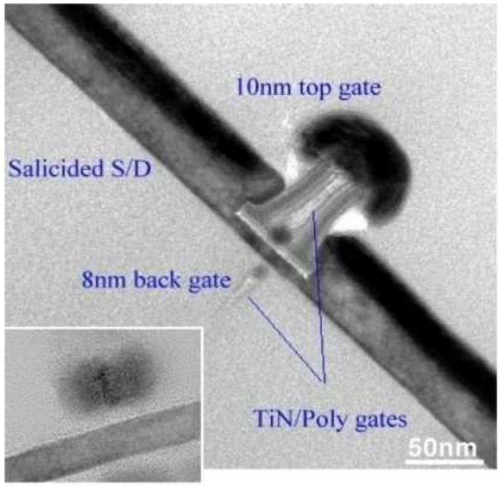
→ **Excellent electrostatic control** → **Better I_{on}/I_{off} ratio**

→ **Undoped film (no more doping fluctuation)** → **μ ↗**

→ **The reduction of channel length** → **New transport properties**

↳ **To take advantage of this new devices, designers need a model, particularly a compact model to design future circuits.**

Our objective

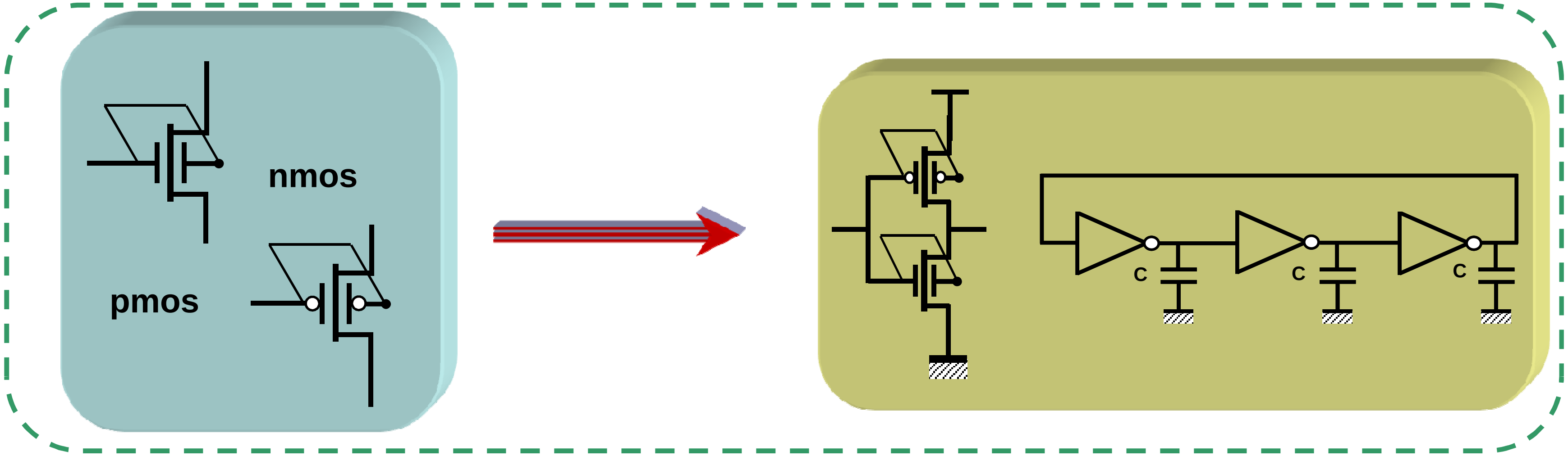


M. Vinet *et al* CEA-LETI 2007

Downscaling of MOSFET to nanometric dimensions → **Emergence of physical phenomena such as ballistic transport**

Evaluation of the ballistic transport on circuit performances

Verilog-A environment



OUTLINE

- I) Introduction
- II) Physics of ballistic transport
- III) Our compact model
- IV) Device and circuit results
- V) Conclusion

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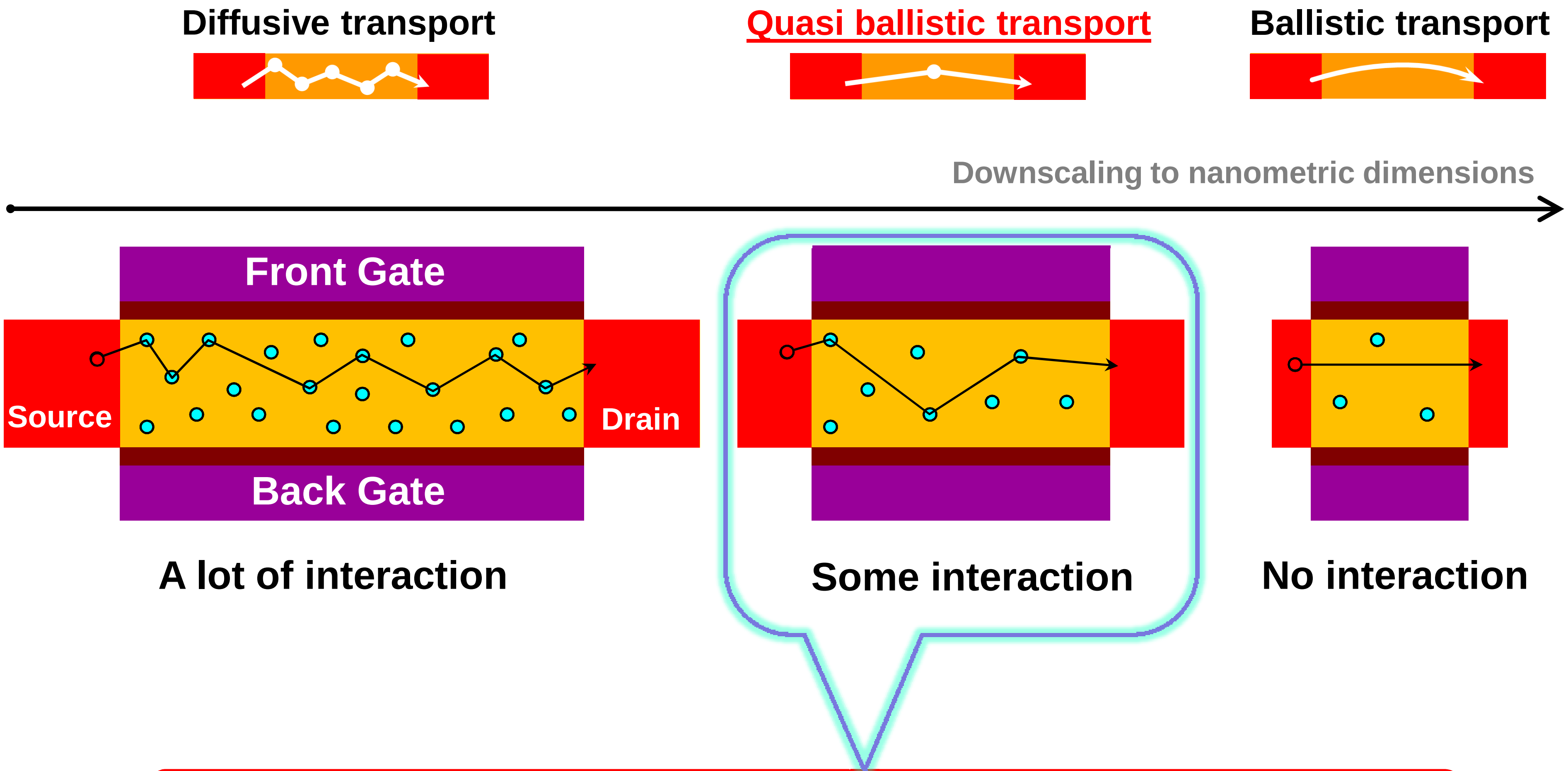
II.1) Schematic view of electronic transport



Diffusive transport

Quasi ballistic transport

Ballistic transport

Downscaling to nanometric dimensions

A lot of interaction

Some interaction

No interaction

The main difficulty is to implement an unified compact model which links the diffusive to the ballistic transport.

○ **Impurities**

● **Electron**

II.1) Schematic view of electronic transport

Diffusive transport

Quasi ballistic transport

Ballistic transport

The well adapted parameter is the mobility (μ)

The well adapted parameter is the mean free path (λ)

Boltzmann Transport Equation

Current continuity

Closure relation on average energy

Drift Diffusion model [1]

$$\mathbf{J}_n = q.D_n.\nabla_{\mathbf{r}} n + q.n.\mu_n.\mathbf{E}$$

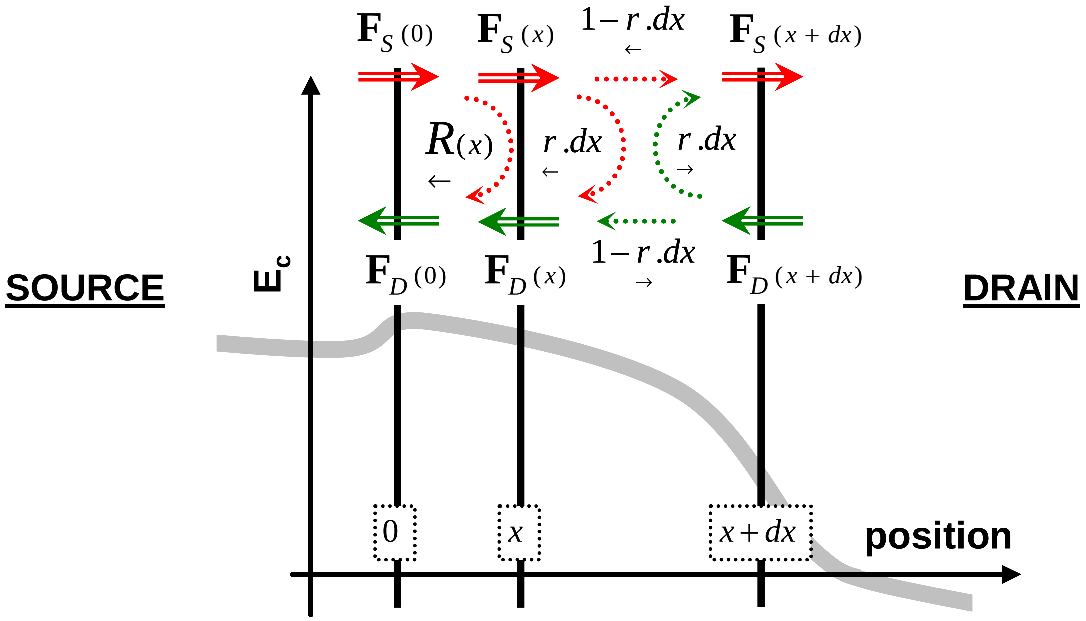
One flux theory or McKelvey theory [2]

Our model is based on this formalism !!!

[1] T. Grasser *et al* TED Feb 2003

[2] J. P. McKelvey *et al* Phys. Rev 1961

II.3) Physical assumption on backscattering coefficient



Physical assumption [1-2] :

- Non degenerate semiconductor
- Constant electric field
- No generation or recombination

$\mathbf{F}_{D(x)}$ = Drain flux

$\mathbf{F}_{S(x)}$ = Source flux

$\underset{\leftarrow}{R}_{(x)}$ = Backscattering coefficient

$\underset{\leftarrow}{r}$ = scattering probabilities

$\mathbf{F}_{D(x)}/\mathbf{F}_{S(x)} = \underset{\leftarrow}{R}_{(x)}$

For constant electric field :

$$\underset{\leftarrow}{R} = \frac{\underset{\leftarrow}{r}}{\sqrt{\underset{\leftrightarrow}{r}^2 - \underset{\rightarrow}{r}.\underset{\leftarrow}{r}}.\mathbf{coth}\left(x.\sqrt{\underset{\leftrightarrow}{r}^2 - \underset{\rightarrow}{r}.\underset{\leftarrow}{r}}\right)+\underset{\leftrightarrow}{r}}$$

with : $\underset{\leftrightarrow}{r} = (\underset{\rightarrow}{r}+\underset{\leftarrow}{r})/2$

With : $\underset{\rightarrow}{r} = \lambda^{-1} - \frac{q.E}{k_B.T_L}$ **and** $\underset{\leftarrow}{r} = \lambda^{-1}$

$$\underset{\leftarrow}{R} = \frac{\lambda^{-1}}{\left(L.\frac{kT}{q.V_{DS}}\right)^{-1}.\left(\frac{1}{1-e^{-\frac{q.V_{DS}}{k.T}}}\right)+\lambda^{-1}}$$

$$\boxed{\underset{\leftarrow}{R} = \frac{L_{kT}}{L_{kT}+\lambda}}$$

M. Lundstrom
EDL Jul. 1997

[1] J. P. McKelvey *et al* Phys. Rev 1961

[2] M.Lundstrom *et al* TED 2002

II.4) Current model

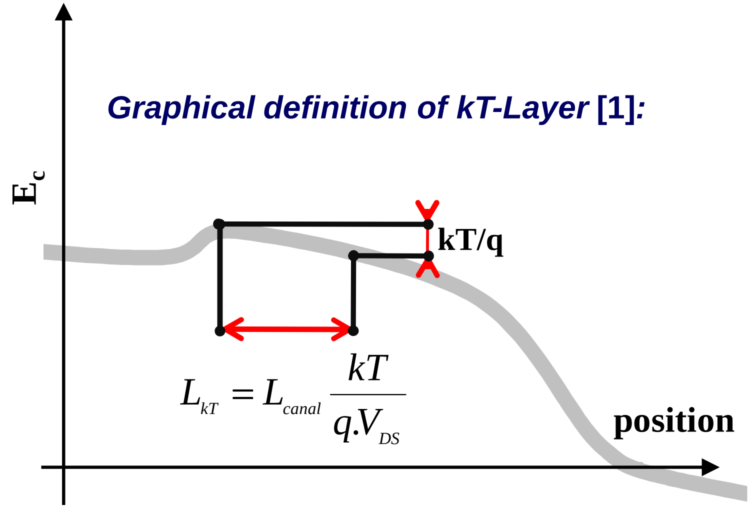
The Backscattering coefficient [1]:

$$R = \frac{L_{kT}}{L_{kT} + \lambda}$$

kT-Layer: the critical distance over which scattering events modify the current

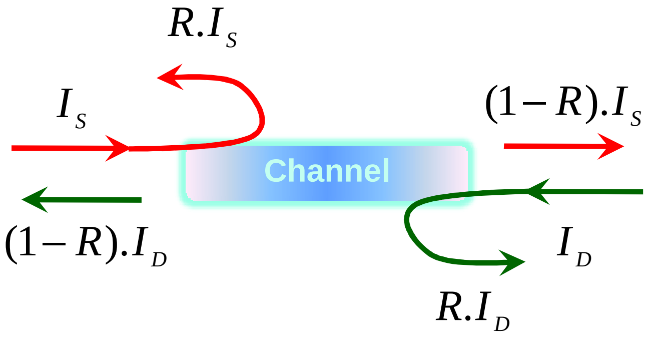
mean free path: effect of scattering process

Graphical definition of kT-Layer* [1]*:



$$L_{kT} = L_{canal}\frac{kT}{q.V_{DS}}$$

We obtain the current versus potential characteristics in presence of scattering processes:



$$\boxed{I = W.C_{ox}.(V_{GS} - V_T).v_{th}.\left(\frac{1-R}{1+R}\right)\left(\frac{1-e^{-qV_{DS}/k.T}}{1-\left(\frac{1-R}{1+R}\right)e^{-qV_{DS}/k.T}}\right)}$$

with : $v_{th} = \sqrt{\frac{2.k.T}{\pi.m*}}$ **is the thermal velocity**

W **:** gate width **/** C_{ox} **:** gate oxide capacitance**/** V_{GS} **:** gate to source voltage **/** V_{DS} the drain to source voltage
V_T **:** threshold voltage **/** k the Boltzmann constant **/** q **:** electron charge **/** T the lattice temperature.

[1] M.Lundstrom *et al* JCE 2002

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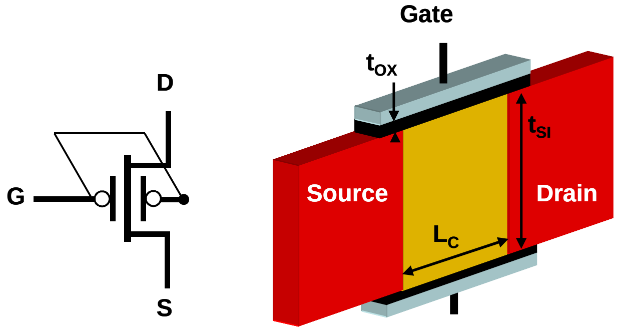
III.1) Verilog-A model

$$\frac{1-R}{1+R} = \frac{dfp}{2.L_{kT}+dfp} \quad \textbf{and} \quad dfp(\varepsilon_{bal}) = v_{bal}.\tau_{tot}$$

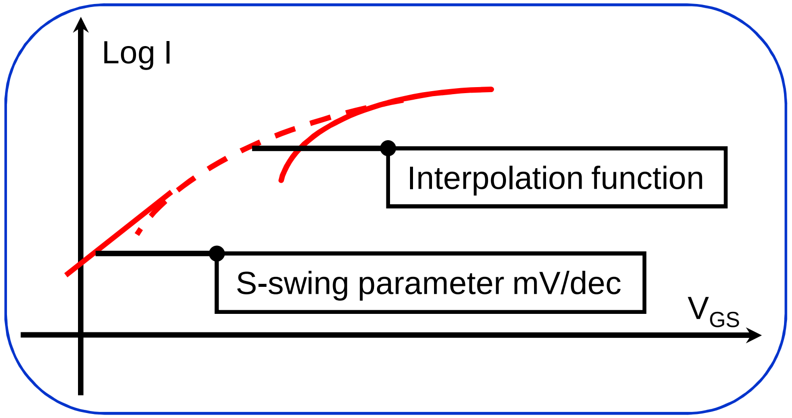
- Ionized impurity, optical and acoustic phonon are taking to account here.

$$V_T = V_{th} - \Delta V_T$$

Symmetrical Double gate



$$I = \boxed{2}.W.f(S).C_{ox}.(V_{GS} - \boxed{V_T}).v_{th}.\boxed{\left(\frac{1-R}{1+R}\right)}\left(\frac{1-e^{-qV_{DS}/k.T}}{1-\left(\frac{1-R}{1+R}\right)e^{-qV_{DS}/k.T}}\right)$$



Interpolation function

S-swing parameter mV/dec

III.2) Short channel effects

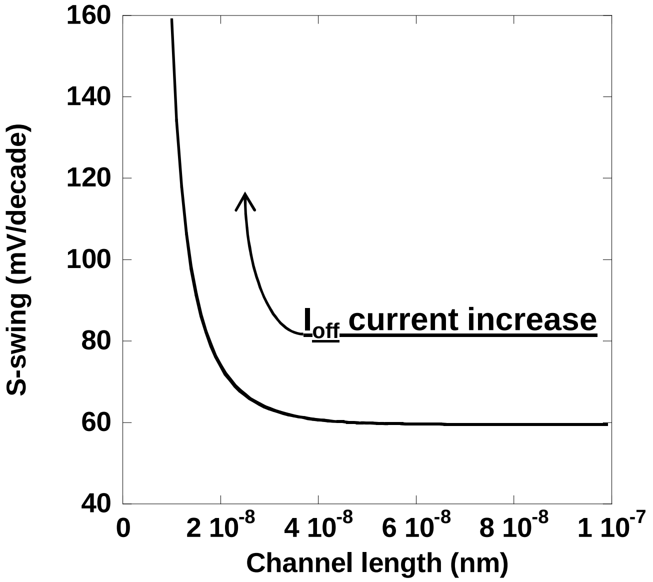
Threshold voltage use the Suzuki's model and our interpolation function [1]:

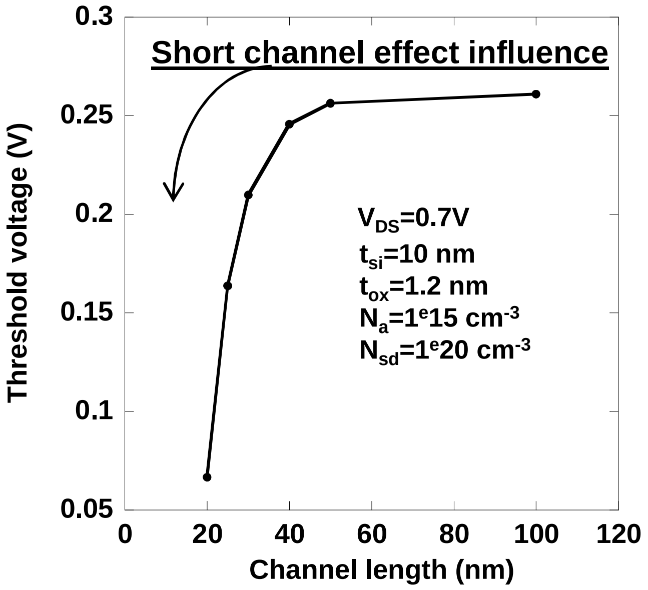
$$I = 2.W.f(S).C_{ox}.(V_{GS} - V_T).v_{th}.\left(\frac{1-R}{1+R}\right)\left(\frac{1-e^{-qV_{DS}/k.T}}{1-\left(\frac{1-R}{1+R}\right)e^{-qV_{DS}/k.T}}\right)$$

interpolation function

S_swing parameter

$$V_T = V_{th} - \Delta V_T$$





Finally our model describes all short channel effects by using the analytical Suzuki's approach.

[1] K Suzuki *et al* TED 1996

III.3) Dynamical mean free path

As described before the backscattering coefficient was:

$$R = \frac{L_{kT}}{L_{kT} + \lambda}$$

We introduce a new characteristic length (*dfp*)

$$R = \frac{L_{kT}}{L_{kT} + dfp}$$

The definition of this dynamical mean free path (*dfp*) [1] is:

$$dfp(\varepsilon_{bal}) = v_{bal}(\varepsilon_{bal}).\tau_{tot}(\varepsilon_{bal})$$

$$\varepsilon_{bal} = \frac{3}{2}.k.T + q.V_{DS}$$

$$v_{bal}(\varepsilon_{bal}) = \sqrt{\frac{2.\varepsilon_{bal}}{m*}}$$

$$\tau_{tot}(\varepsilon_{bal}) = \frac{1}{\dfrac{1}{\tau_{imp}(\varepsilon_{bal})} + \dfrac{1}{\tau_{phonon}(\varepsilon_{bal})}}$$

$$\tau_{imp}(\varepsilon_{bal}) \propto \varepsilon_{bal}^{\frac{3}{2}} \qquad \tau_{phonon}(\varepsilon_{bal}) \propto \varepsilon_{bal}^{-\frac{1}{2}}$$

The dynamical mean free path is a local free path of ballistic carriers.
It represents the average distance to be crossed before the next scattering event.

[1] E Fuchs et al IEEE TED Oct 2005

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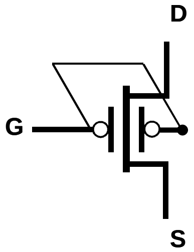
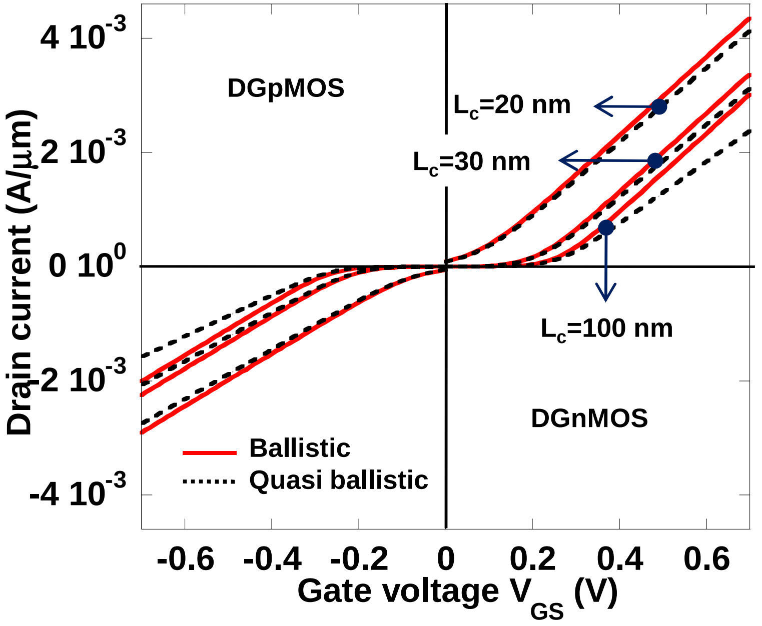
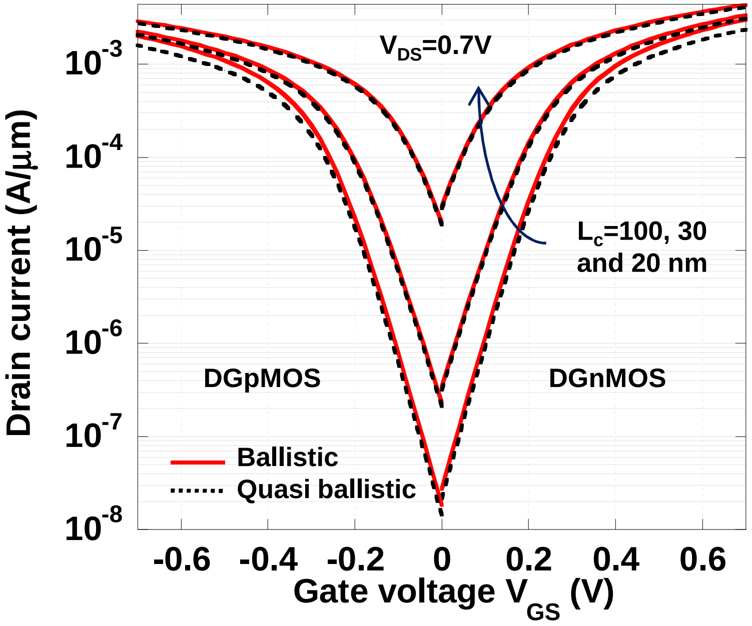
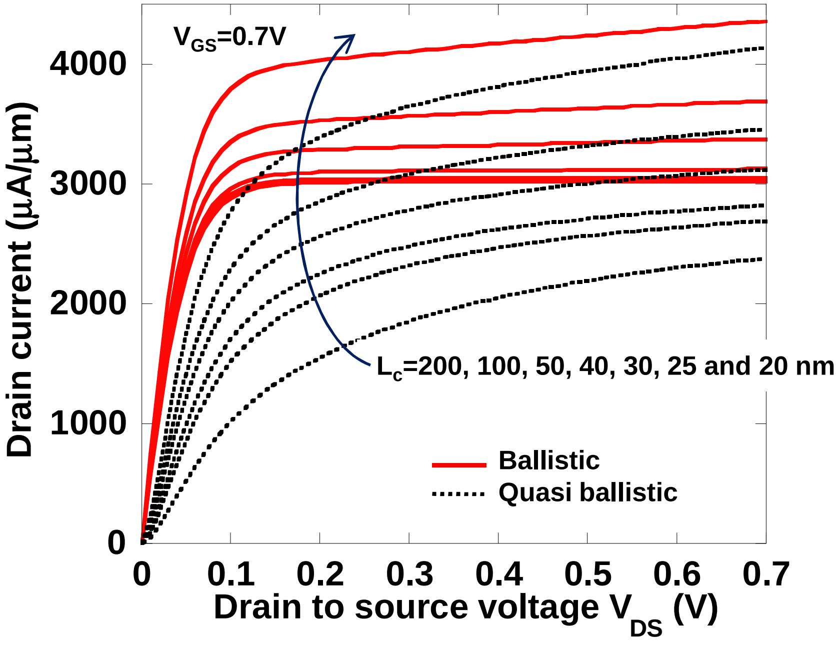
IV.1) Device simulation DGnMOS and DGpMOS





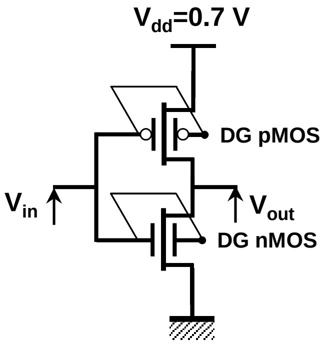


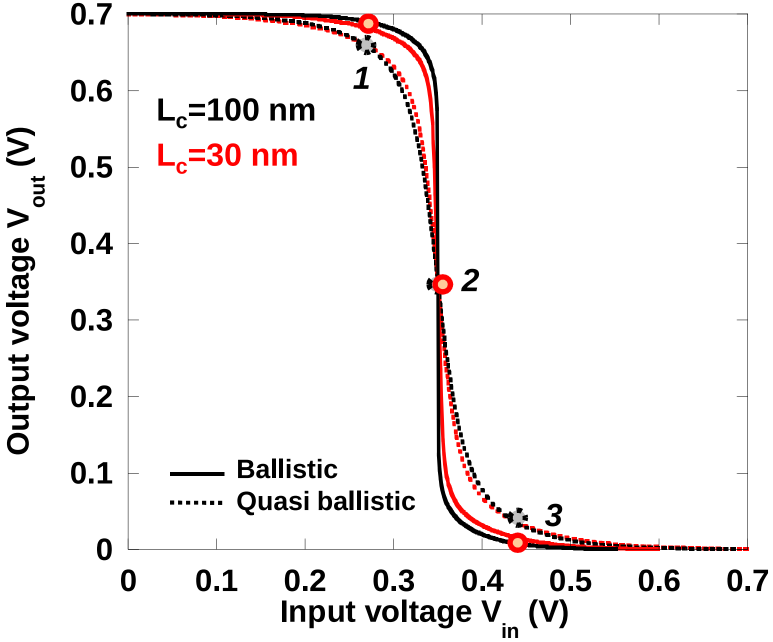


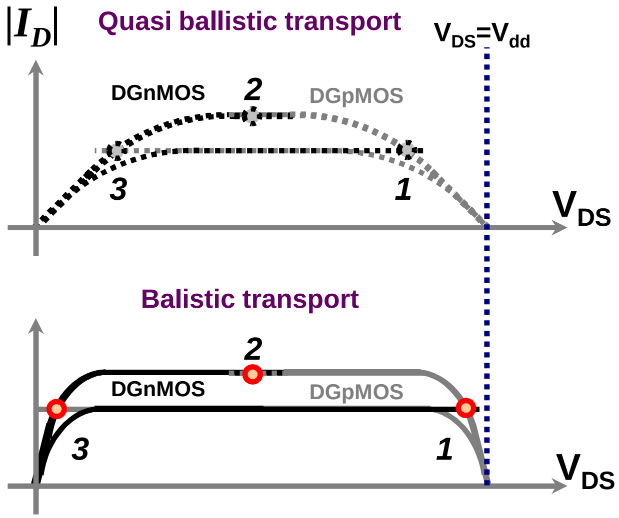
- The drain current is independent of the channel length in ballistic case, except for the smallest lengths for which short channel effects are exacerbated.

- In contrast to the ballistic case, the quasi-ballistic transport has the same behavior compared to diffusive transport.

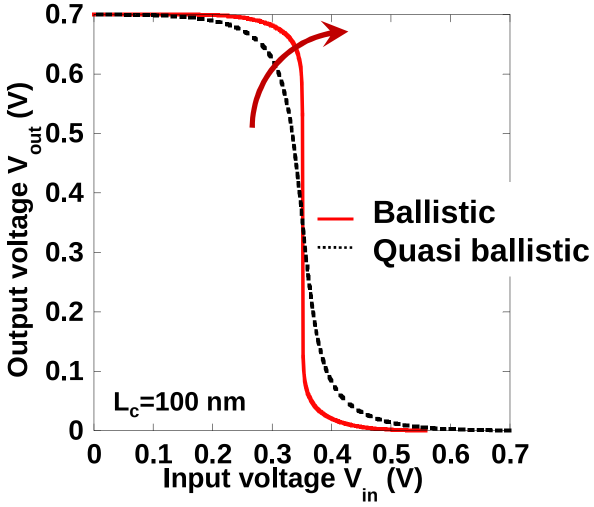
IV.2) CMOS inverter

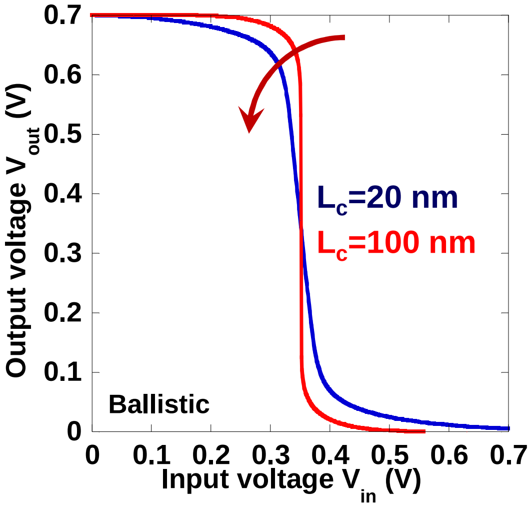




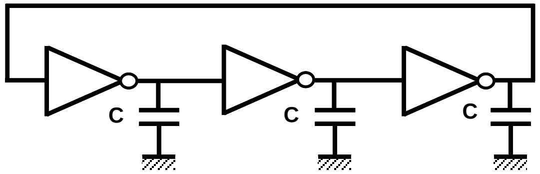


Quasi-ballistic → Ballistic → Ballistic with SCE

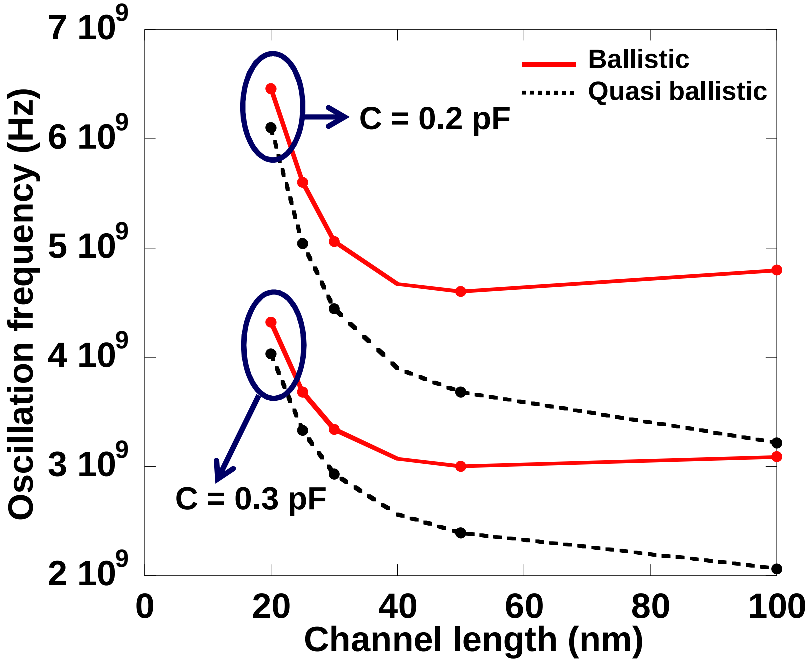


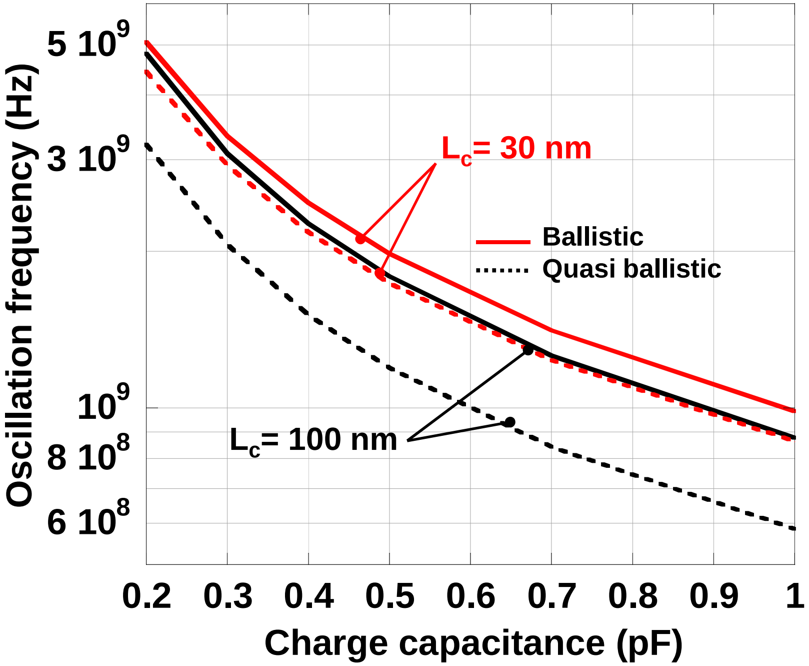


IV.3) Ring oscillator



$$f^{-1} = 2.N.t_d = C.\int_{0.9Vdd}^{0.1Vdd} \frac{1}{I} dV_{DS}$$





-Oscillation frequency is strongly impacted by short channel effects and the type of transport (Ballistic/Quasi-Ballistic)

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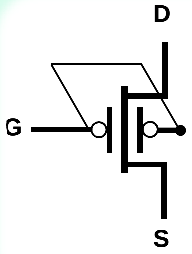
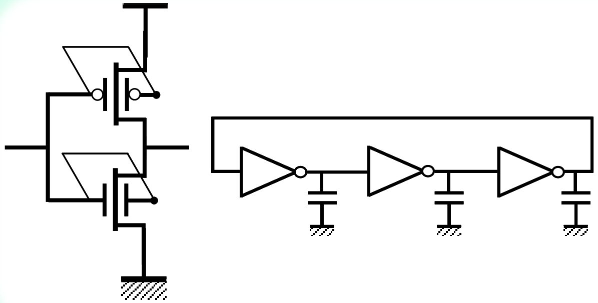
CONCLUSION



→ A unified compact model for DGMOS taking into account Ballistic / Quasi-Ballistic transport and short channel effect has been developed and implemented in Verilog-A environment to obtain a complete description of current characteristics (sub 32 nm node)



→ Our simulation results proved that the Ballistic transport improves the static and transient performances of circuit elements.

This work also demonstrates the feasibility of a simulation study of Ballistic / Quasi-Ballistic transport at circuit level and <u>highlights the direct relation between the type of transport and circuit performances</u>

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THANK YOU FOR ATTENTION

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