Influence of gate capacitance on CNTFET performance using Monte Carlo simulation

H. Cazin d'Honincthun,

S. Retailleau, A. Bournel, P. Dollfus, J.P. Bourgoin*

Institut d'Electronique Fondamentale (IEF)
UMR 8622 – CNRS-Université Paris Sud 11, Orsay, France
***Laboratoire d'électronique moléculaire, CEA/DSM/DRECAM/SPEC, CEA Saclay, France**

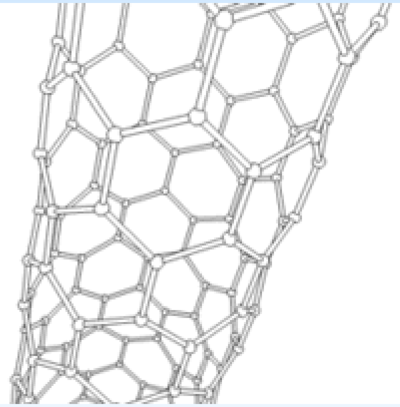
UPS

Plan

- Carbon nanotubes: high potential material
- Carbon nanotubes: Model for calculations (Monte Carlo)
- Evaluation of Mean Free Path
- Carbon nanotube field effect transistor simulation

Potentialities of Carbon nanotubes

Charge transport and confinement



- ✓ Charge transport is quasi-ballistic: few interactions
- ✓ Charge confinement (1D): good control of electrostatics

No dangling bonds

- ✓ Possibility to use High K material for oxide

Band structure « quasi » symmetric

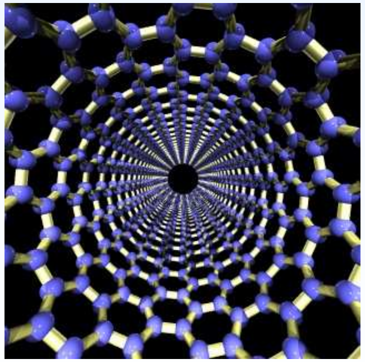
- ✓ Transport properties identical for electron and hole (same m*)

Carbon nanotubes can be either metallic as well as semi-conducting

- ✓ All-nanotube-based electronic is possible

Plan

- ➢ Carbon nanotubes: high potential material
- ➢ Carbon nanotubes: Model for calculations (Monte Carlo)
- ➢ Evaluation of Mean Free Path
- ➢ Carbon nanotube field effect transistor simulation



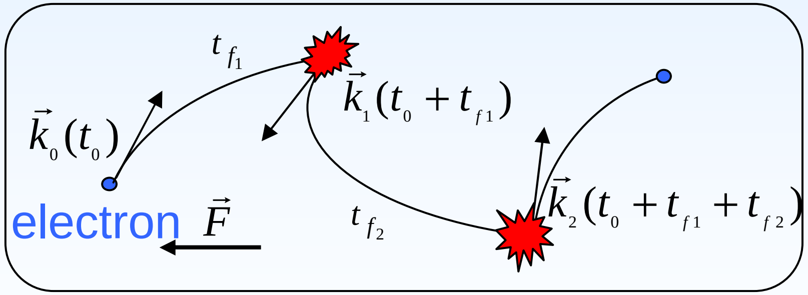
Particle Monte-Carlo method

Study of carrier transport in this work: solving the *Boltzmann* equation by the Monte Carlo method

$$\boxed{\frac{\partial f}{\partial t} = -\vec{v}\cdot\vec{\nabla}_r f - \frac{\vec{F}}{\hbar}\cdot\vec{\nabla}_k f + \left.\frac{\partial f}{\partial t}\right|_{collisions}}$$

Statistical solution :by ***Monte Carlo method***

- $f(\vec{r},\vec{k},t) \rightarrow$ assembly of individual particles
- 1 particle $\Leftrightarrow \vec{r}(t),\vec{k}(t)$
- *N* particles allow us to reconstruct $f\left(\vec{r},\vec{k},t\right)$



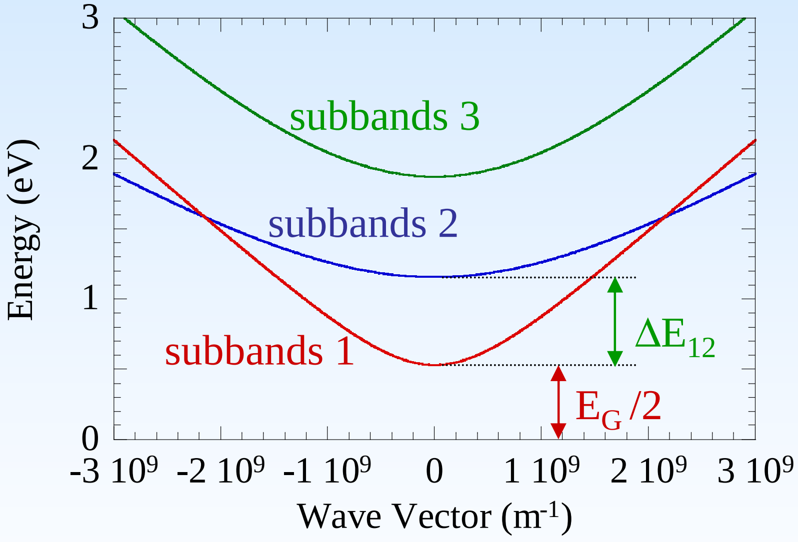
Carrier trajectories:
Succession of free flight and scattering events

scattering rates $\lambda_i\left(\vec{k}\right)$ → random selection of (*Monte Carlo algorithm)* →
- time of free flights t_f
- type of scattering *i*
- effect of scattering (ΔE, θ)

Band structure and phonons

Energy dispersion calculated by:

- Tight-binding
- Zone-folding



Analytical approximation of the three first subbands

$$\frac{\hbar^2 k_z^2}{2\,m_p} = \left[E_p - E_p^m\right]\left[1+\alpha_p\left(E_p - E_p^m\right)\right]$$

Phonon dispersion curves calculated by zone folding method

Approximation

➢ **Longitudinal** acoustic and optical **modes** are considered as **dominant** like in graphene

Analytical approximation of dispersion curves *[Pennington, Phys. Rev. B 68, 045426 (2003)]*

+ RBM phonon ($E_{RBM} \approx$ Cst./d_t)

[M. Machon et al., Phys. Rev. B 71, 035416, (2005)]

Ex: Tube index n=19, E_{RBM}=19 meV

Scattering Events Calculation

- **Scattering rates :** 1st order Perturbation Theory by deformation potential model

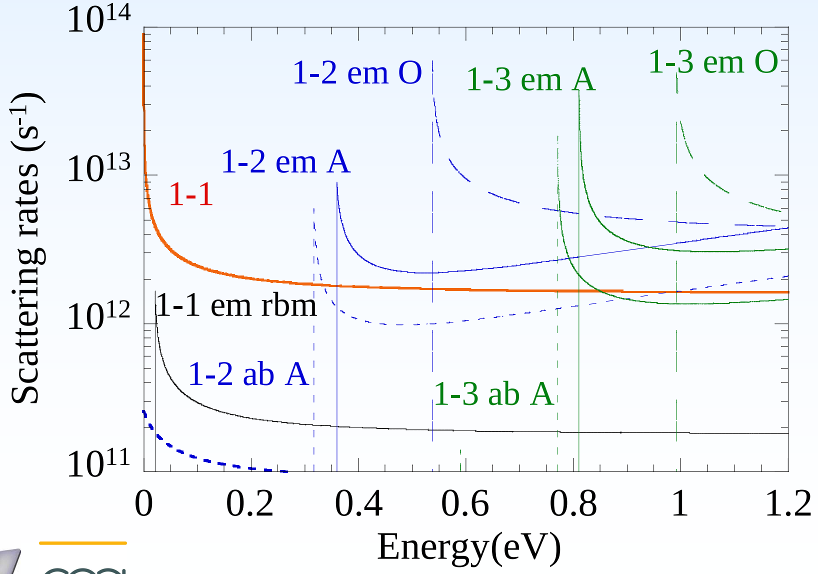
with: $\boldsymbol{D_{aco}} = 9$ eV [*L. Yang, M.P. Anantram et al. Phys. Rev. B* ***60****, 13874 (1999)*]
$\boldsymbol{D_{RBM}} = 0.65$eV/cm *(for n = 19)* [*M. Machon et al., PRB 71, 035416 (2005)*]

☞ **Intrasubband acoustic scattering** ➡ ***Elastic*** process

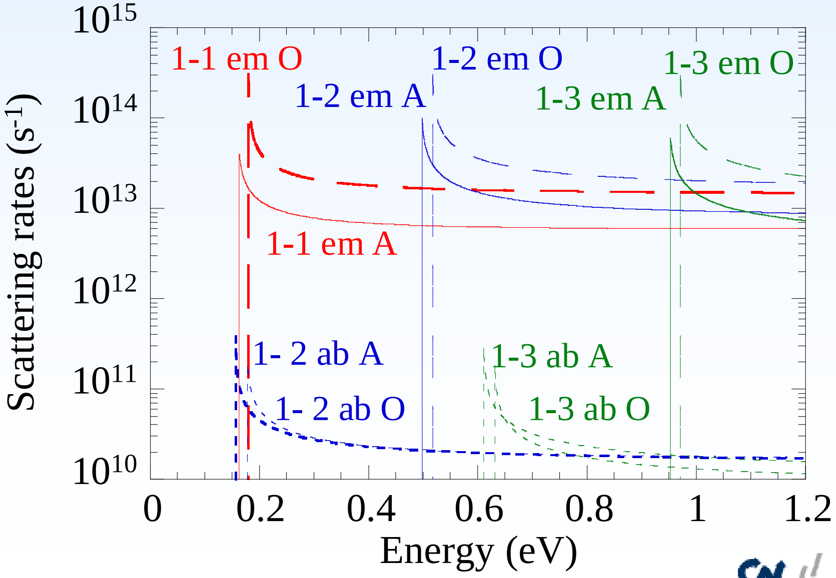
☞ **Intersubband transition** ➡ ***Inelastic*** process $(E = \hbar\omega)$

$\boldsymbol{n} = 19$

intravalley scattering from subband 1

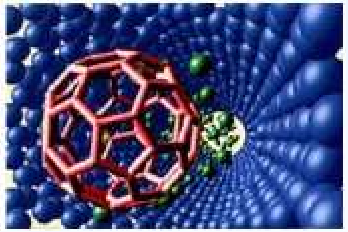


intervalley scattering from subband 1

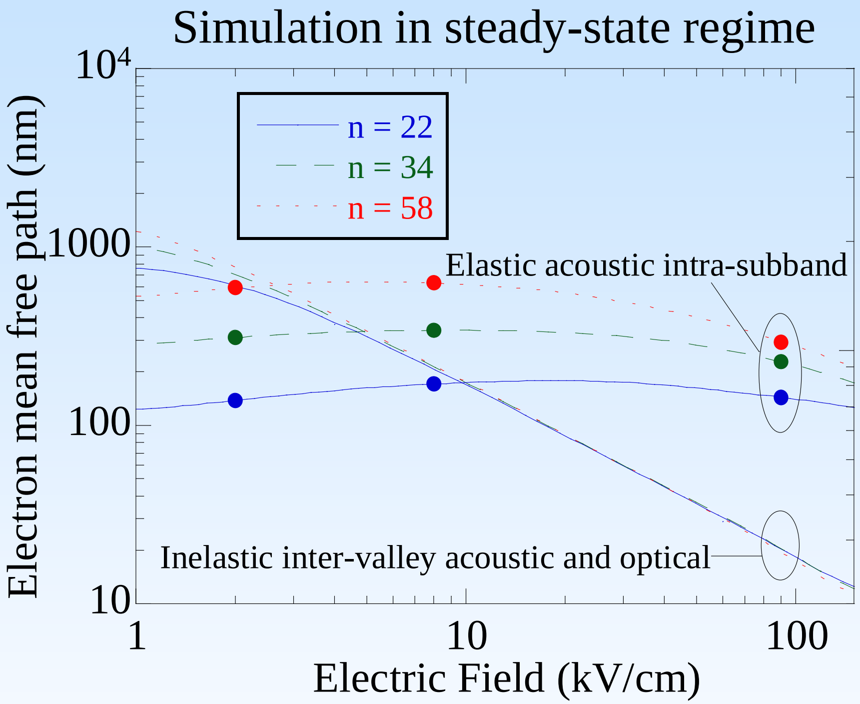


Plan

- Carbon nanotubes: high potential material
- Carbon nanotubes: Model for calculations (Monte Carlo)
- Evaluation of Mean Free Path
- Carbon nanotube field effect transistor simulation



Mean Free Path



The mean free path depends on diameter and electric field :

- ☞ **l_{MFP}=100-600 nm for elastic scattering**
- ☞ **l_{MFP}=1000-20 nm for inelastic scattering**

Agreement with experimental works (L. field:300-500 nm H. Field: 10-100nm)

Potential of quasi-ballistic transport in the low-field regime

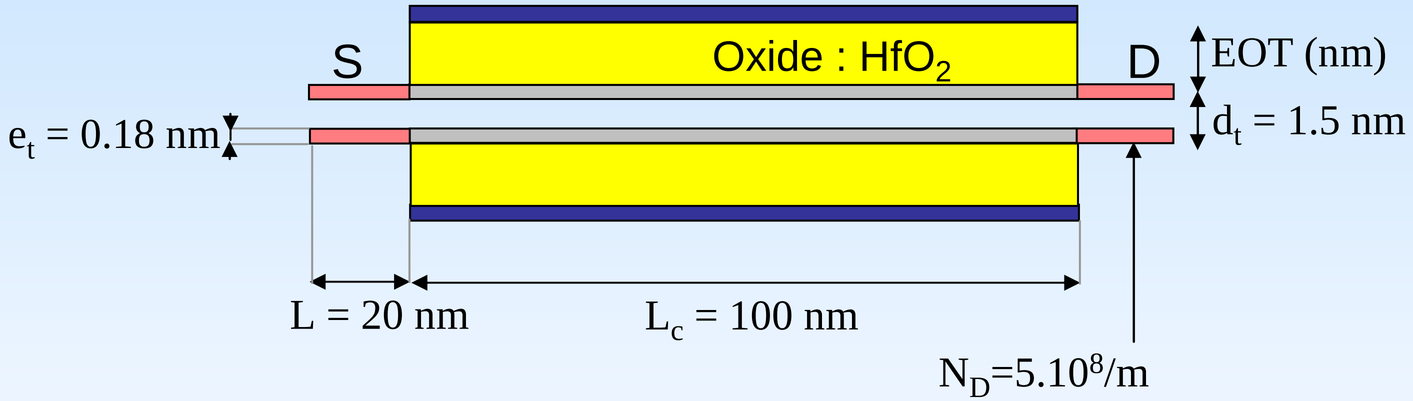
UPS

Plan

- Carbon nanotubes: high potential material
- Carbon nanotubes: Model for calculations (Monte Carlo)
- Evaluation of Mean Free Path
- Carbon nanotube field effect transistor simulation

The modelled transistor

Coaxially gated carbon nanotube transistor with heavily-doped source drain extensions CNTFET

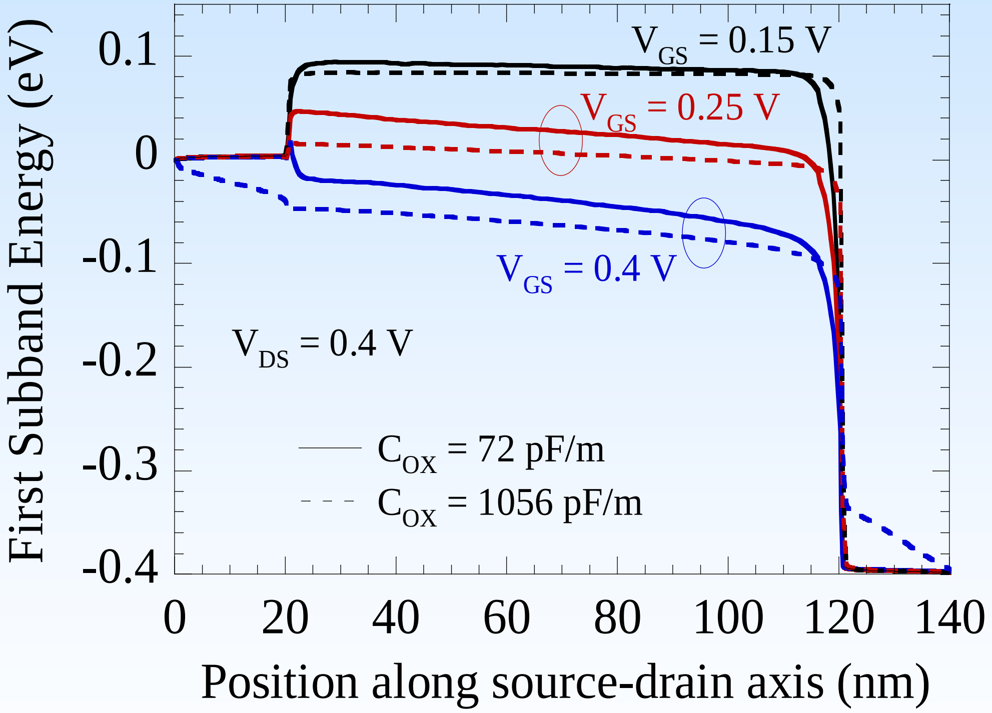


Characteristics:

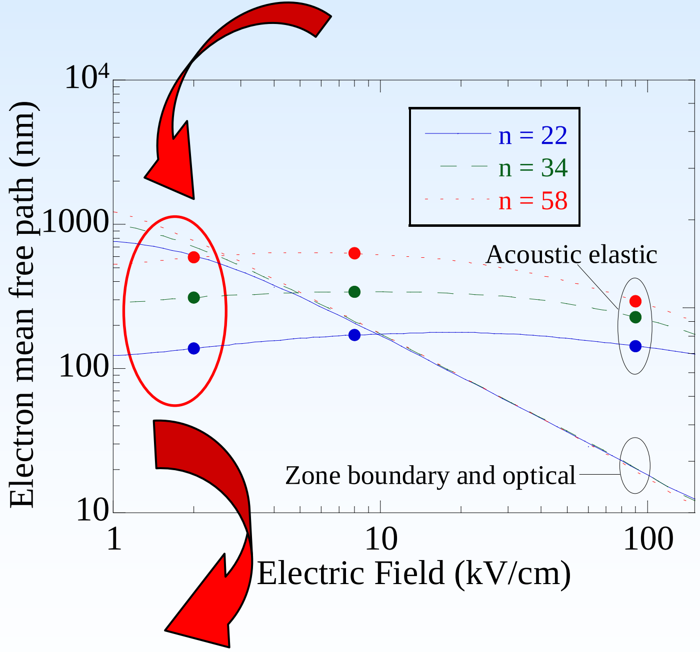
- Zigzag tube (19,0) - d_t = 1.5nm – E_G = 0.55eV
- Cylindrically gated
- Ohmics Contacts (heavily n-doped)
- Intrinsic channel
- High K gate insulator HfO_2 (*EOT* = 16, 1.4, 0.4, 0.1 nm - C_{OX} = 72, 210, 560,1060 pF/m)

Conduction band

First subband energy profile



Weak field in the channel due to strong electrostatic gate control



Weak field in the channel ➡ **quasi ballistic** transport

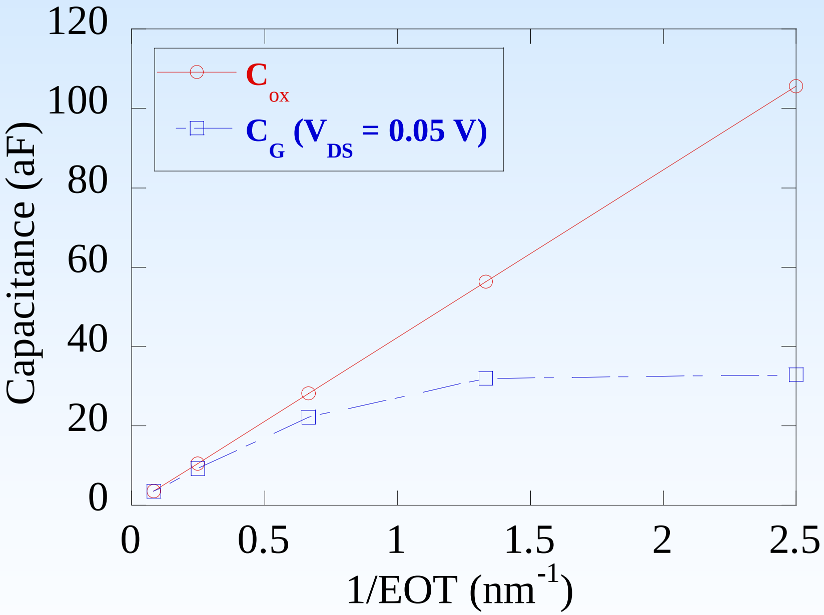
Hugues Cazin d'Honincthun – URSI - 20/03/2007

Capacitive effects

Weak Field ⟺ 1D low density of states ⟹ Channel potential is fixed

Determination of C_G for low V_{DS}: $$C_G = \frac{dQ}{dV_{GS}} \qquad C_{OX} = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln\left(\frac{e_{ox}+r_{dt}}{r_{dt}}\right)}$$

Evolution of C_{ox} and C_G as a function of 1/EOT



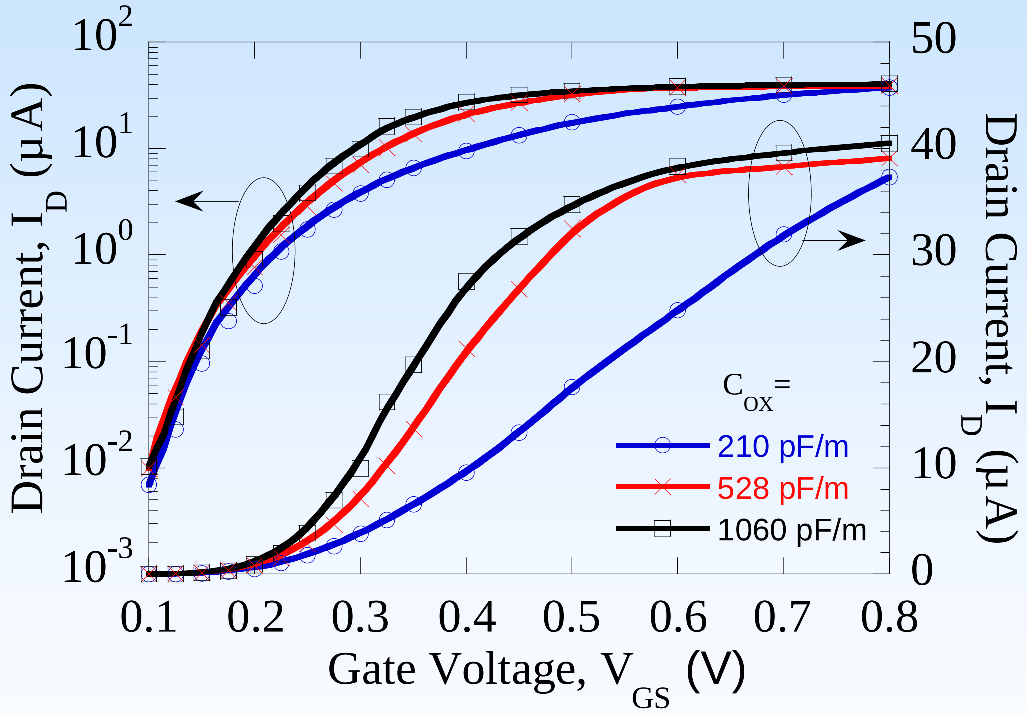
Reminder : $$\frac{1}{C_G} = \frac{1}{C_{ox}} + \frac{1}{C_Q}$$

C_G leads towards C_Q for $C_{ox} >> C_Q$

← ≈ C_G tends towards 4pF/cm

For $C_{ox} >> C_Q$ ⟹ quantum capacitance limit

I_D-V_{GS} Characteristics

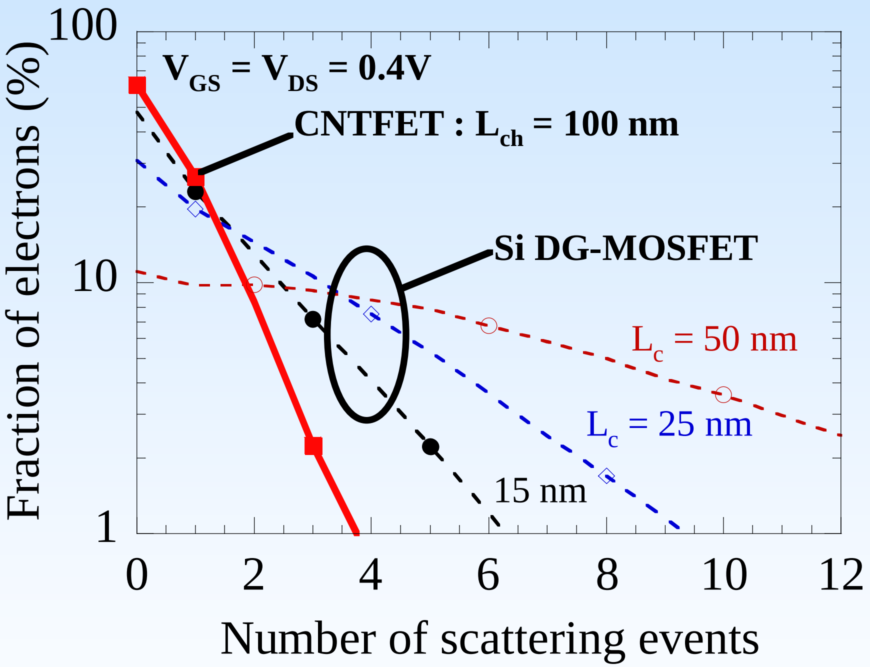


Expected result : I_D increases with oxide capacitance C_{ox} but limited enhancement for high C_{OX} values

UPS

Evaluation of Ballistic Transport

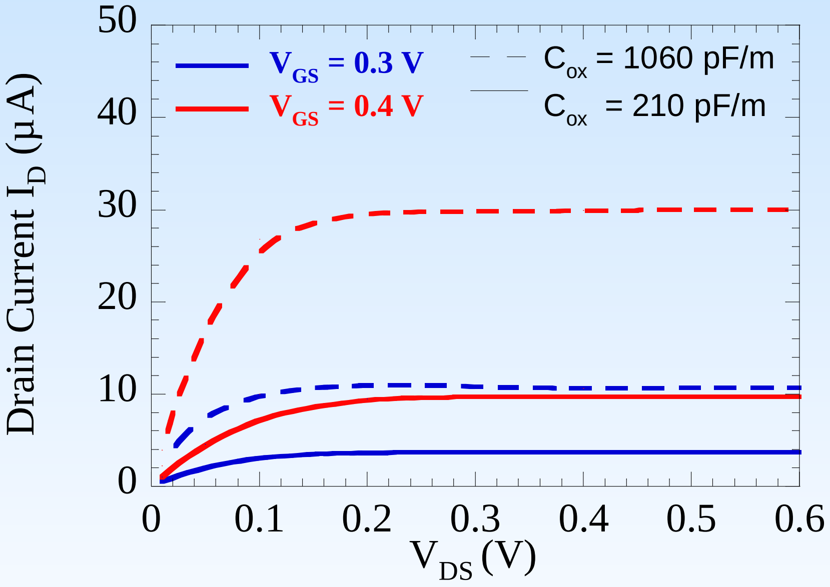
Unstrained Si. DG-MOSFET **vs** c-CNTFET



CNTFET : 70% of ballistic electrons at the drain end for **L_{ch} = 100nm**

Unstrained Si DG : 50% of ballistic electrons pour **L_{ch} = 15 nm**

I_D-V_{DS} characteristics



Device parameters extracted from simulation (I_{off}=0.1nA)

C_{OX} (pF/m) /EOT(nm)	210/ 1.4	560/ 0.4	1060/ 0.1	Expe.* 1.5
S (mV/dec)	70	65	60	70
I_{ON} (µA)	24	40	44	5
g_m (µS)	32	62	100	20

V_{DD} = 0.4V

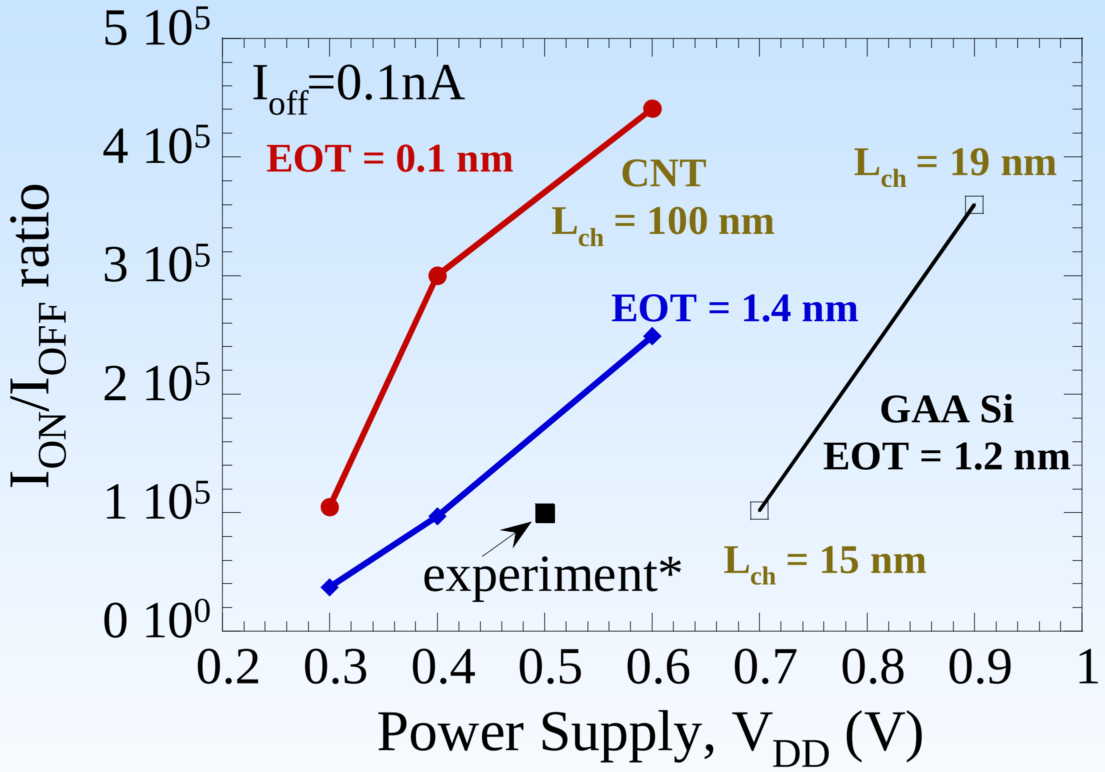
$I_{ON} \approx 10 - 30$ µA. $I_{ON}/I_{OFF} \approx 510^{4} - 510^{5}$

High values of S and g_m are obtained

Acceptable agreement with experiments

* *H. Dai, Nano Letter, vol.5, 345, (2005) : L=80nm, EOT=1.5nm*

I_{ON}/I_{OFF} ratio (V_{DD})



Performances CNT for L_C=100nm and V_{DD}<0.4V

⇕

Performances Si for L_C=15nm and V_{DD}>0.7V

* *H. Dai, Nano Letter, vol.5, 345, (2005) : L=80nm, EOT=1.5nm*

Conclusion

This Monte Carlo simulation of a CNTFET shows excellent performances:

- Excellent electrostatic gate control (quantum capacitance regime)
- High fraction of ballistic electrons in the transistor channel
- High performances at relatively low power supply