Analytical modeling of nano MOSFETs in the quasi ballistic regime : beyond the drift diffusion approximation

R. Clerc,
G. Ghibaudo

P. Palestri,
L. Selmi

IMEP-LAHC
Grenoble Institute of Technology
France

DIEGM
University of Udine
Italy

Transport in Nano MOSFET (L < 20 nm) challenges Compact Modeling

Since the pioneering work of Natori (1994) and Lundstrom (1996), the quasi ballistic regime of transport in nano MOSFETs has been extensively investigated.

However, existing compact model are still based on Drift Diffusion and saturation velocity concepts

« Sophisticated computer simulations using techniques such as full band Monte Carlo and full quantum transport approaches are being used to explore the physics of the ultimate MOSFET, but ***circuit models continue to be based on concepts and approaches developed in the 1960's. »***

M. Lundstrom, Int. SOI Conference, 2006

→ Let us examine the applicability of Quasi Ballistic theories to compact modeling

Outline

The "orthodox" Lundstrom theory

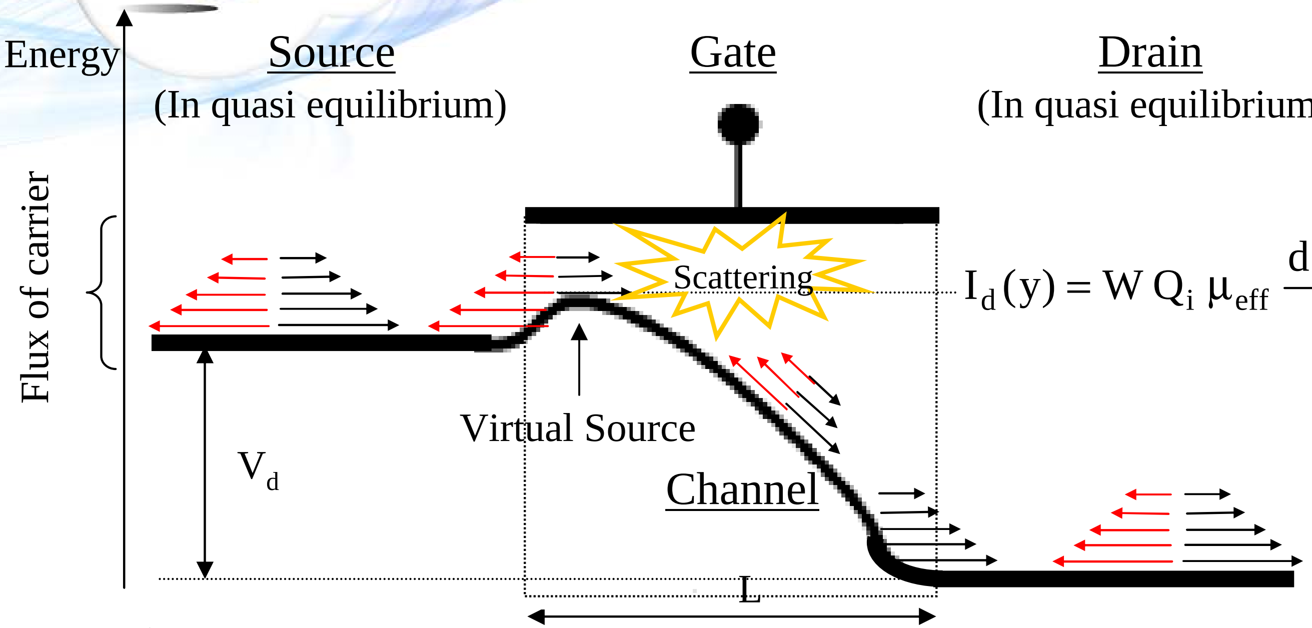
Beyond Lundstrom's theory

Ballisticity extraction from experiments

The “orthodox” Lundstrom theory

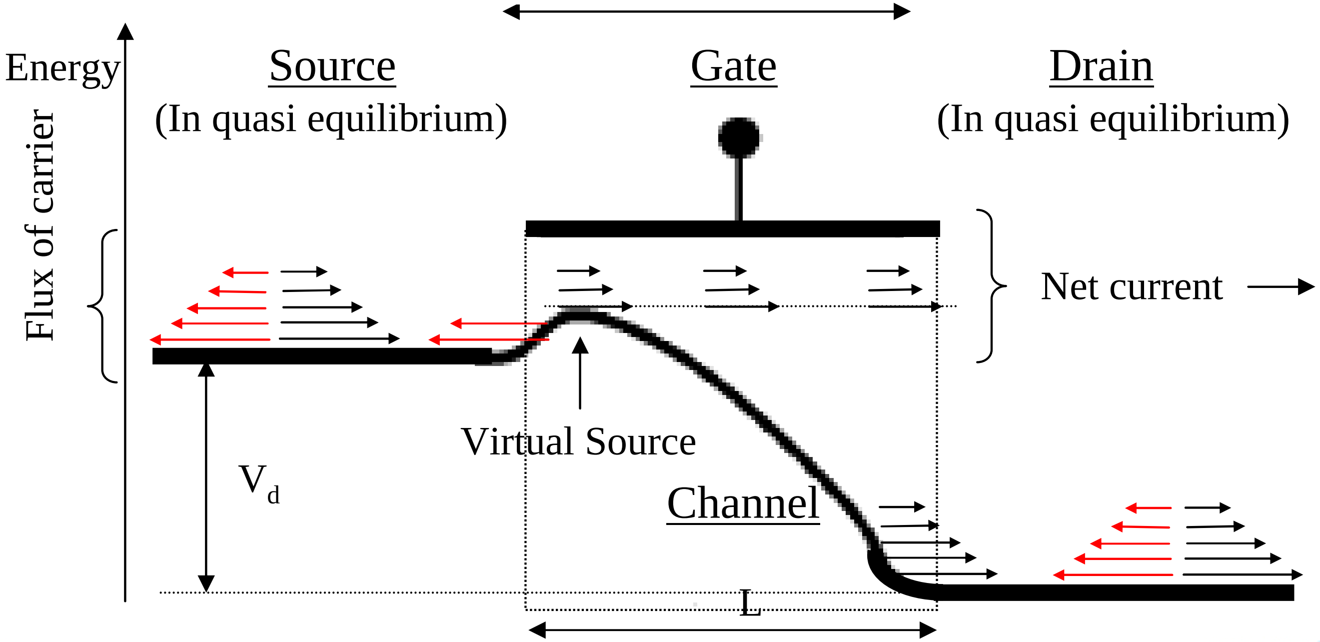
Concept of Ballistic Limit

Transistor in diffusive regime



$$I_d(y) = W\, Q_i\, \mu_{eff} \frac{d\,E_{Fn}}{dy}(y)$$

Transistor in ballistic regime

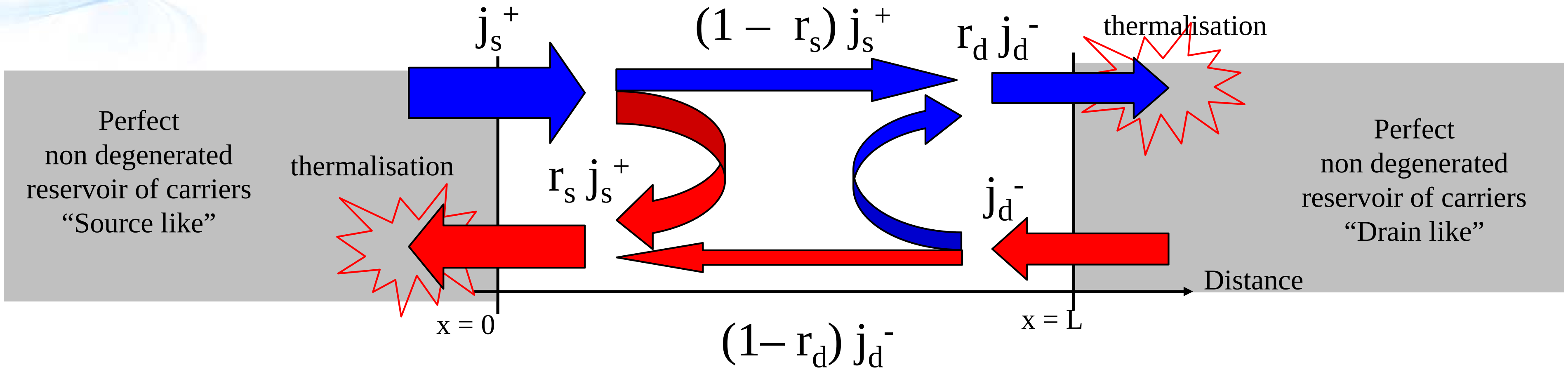


Net current $\longrightarrow$ $\boxed{I_{d\,BAL} \approx W\, Q_i\, V_{inj}}$

Performance are no longer limited by transport along the channel, but by injection at the source end

Concept of Backscattering Coefficient

Using Mc Kelvey flux theory of Transport :



J. P. McKelvey, R. L. Longini and T. P. Brody, « Alternative approach to the solution of added carrier transport problems in semiconductors », Phys. Rev., vol **123** pp. 51-57 (1961).

Assuming an Inversion Charge Q_i at the virtual source controlled by the gate : (like in the Natori's model)

$$\frac{I_d}{W} = \frac{(1-r) - \exp(-eV_d/kT)\,(1-r)}{(1+r) + \exp(-eV_d/kT)\,(1-r)}\, Q_i\, v_{th}$$

$$\boxed{\frac{I_{d\,Sat}}{W} = \frac{1-r}{1+r}\, Q_i\, v_{th}}$$

$$\boxed{\frac{I_{d\,Lin}}{W} = (1-r)\,\frac{Q_i}{2}\, v_{th}\, \frac{e\,V_d}{kT}}$$

A. Rahman and M. S. Lundstrom, « A compact scattering model for the nanoscale double-gate MOSFET », IEEE. TED, vol. 49 p 481 - 489 (2002)

Concept of Backscattering Coefficient

r_{LF} = <u>Back Scattering Coefficient at Low Field (Ohmic Regime)</u>

assuming a constant isotropic mean free path : $\boxed{r_{LF} = \frac{L}{L+\lambda}}$ (using Boltzmann or Fermi Statistics)

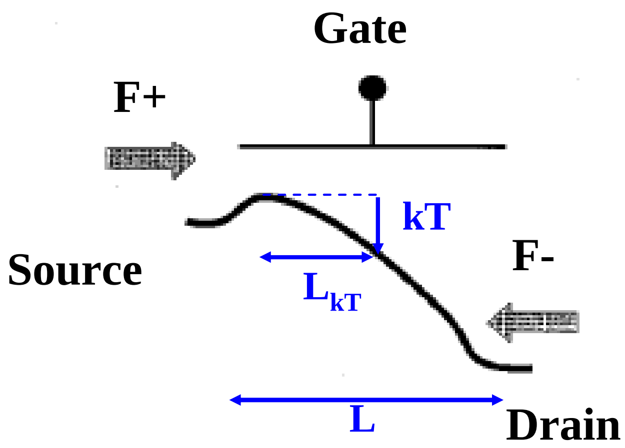
M. Lundstrom, « Fundamentals of Carrier Transport », second edition, Cambridge university press, 2000

When L >>λ, **this is consistent with the Drift Diffusion model :**

$$\frac{I_{d\,Lin}}{W} = (1-r)\frac{Q_i}{2} v_{th} \frac{e\,V_d}{kT} \xrightarrow{L \gg \lambda} \frac{I_{d\,Lin\,DD}}{W} = \frac{1}{L}\mu_{eff}\, Q_i\, V_d \quad \text{if} \quad \boxed{\lambda = \frac{2\mu_{eff}}{v_{th}}\frac{kT}{e}}$$

*M. Lundstrom IEEE EDL **22** p. 293 (2001)*

r_{HF} = <u>Back Scattering Coefficient at High Field (Saturation Regime)</u>



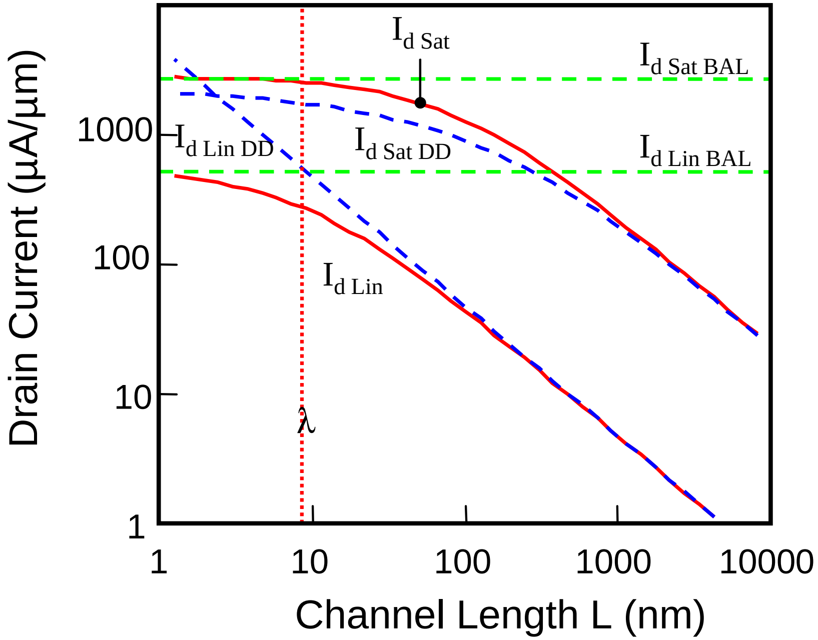
$$\boxed{r_{HF} = \frac{L_{kT}}{L_{kT}+\lambda}} \longrightarrow \boxed{\textit{empirical}}$$

intuited as a generalization of r_{LF} $\quad r_{LF} = \frac{L}{L+\lambda}$

*M. Lundstrom Z. Ren, IEEE TED **49** p.133 (2002)*

Backscattering Coefficient Modeling

In the MOSFET model, we have : $\dfrac{I_{d\,Sat}}{W} = \dfrac{1-r}{1+r} Q_i \, v_{th}$ with $r_{HF} = \dfrac{L_{kT}}{L_{kT} + \lambda}$



When L >>λ, **this is consistent with the Drift Diffusion model :**

$$\frac{I_{d\,Sat\,DD}}{W} = \frac{1}{L} \mu_{eff} \, C_{ox} \frac{(V_g - V_T)^2}{2} \quad \text{if}$$

$$\lambda = \frac{2\mu_{eff}}{v_{th}} \frac{kT}{e}$$ (same expression than in ohmic regime)

and $$\boxed{L_{kT} = L \frac{2\,kT/e}{V_{d\,SAT}} = L \frac{2\,kT/e}{V_g - V_T}}$$

which is in fact **equal to the L_{kT} layer calculated from the Drift Diffusion potential profile !**

$\mu = 200\ cm^2V^{-1}s^{-1}$
$V_{inj} = 1.2 \times 10^5$ m/s
$N_{inv} = 1.45 \times 10^{13}\ cm^{-2}$

- In ohmic regime, Quasi ballistic transport occurs when L ~ λ
- In saturation, Quasi ballistic transport occurs **when L_{kT} ~ λ i.e when L ~ 10 λ**

M. S. Lundstrom and J. H. Rhew Journal of Computational Electronics, vol. ***1*** *pp 481 - 489 (2002).*

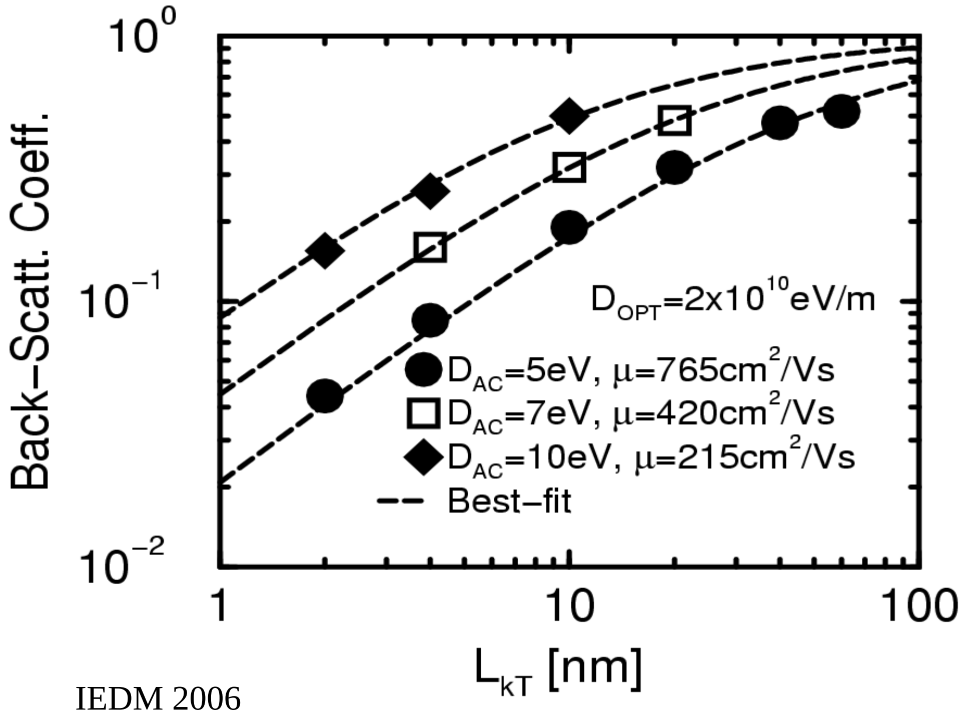
Validation by Monte Carlo Simulation

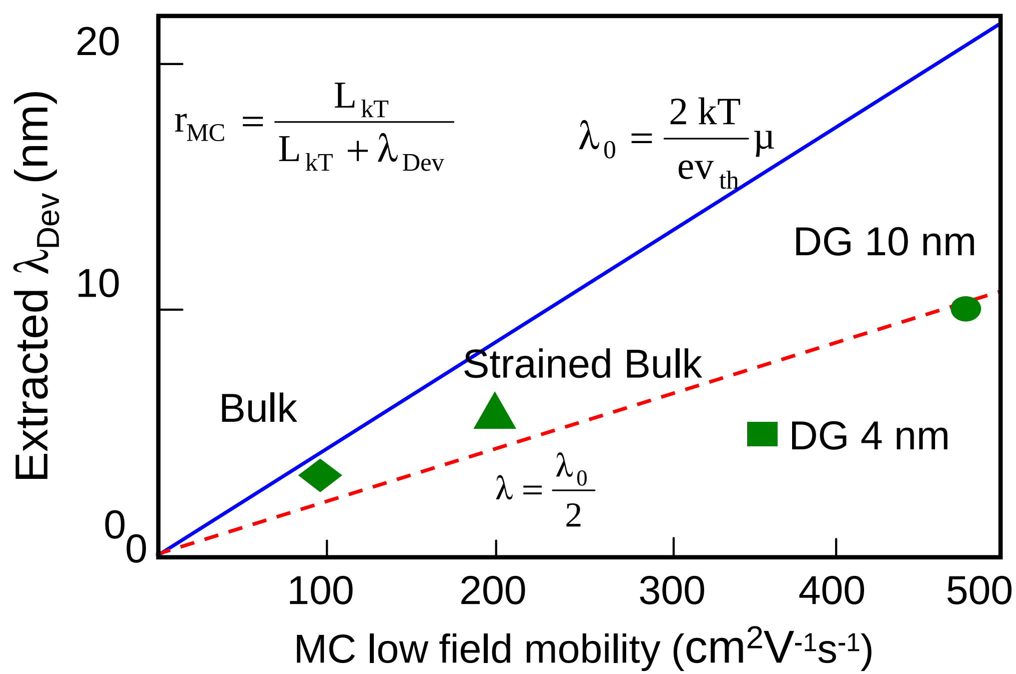
$$r_{HF} = \frac{L_{kT}}{L_{kT} + \lambda} \quad ??$$

$$\lambda_0 = \frac{2\,kT}{e v_{th}} \mu \quad ??$$

r_{HF} extracted is in fact a function of LkT

λ extracted is in fact proportional to μ





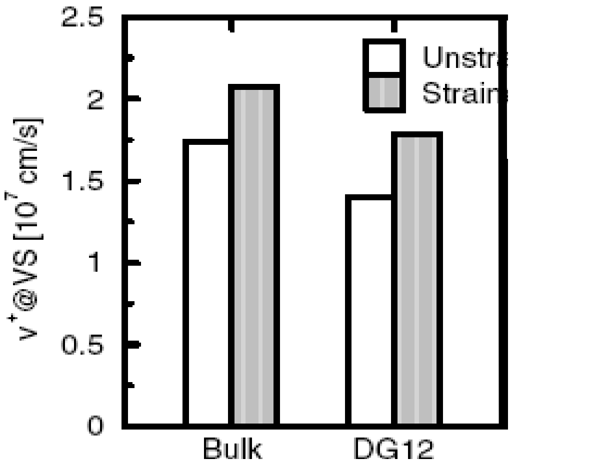
IEDM 2006
« Multi Subband Monte Carlo investigation of the mean free path and of the kT layer in degenerated quasi ballistic MOSFETs »
P. Palestri, R. Clerc, D. Esseni, L. Lucci, L. Selmi

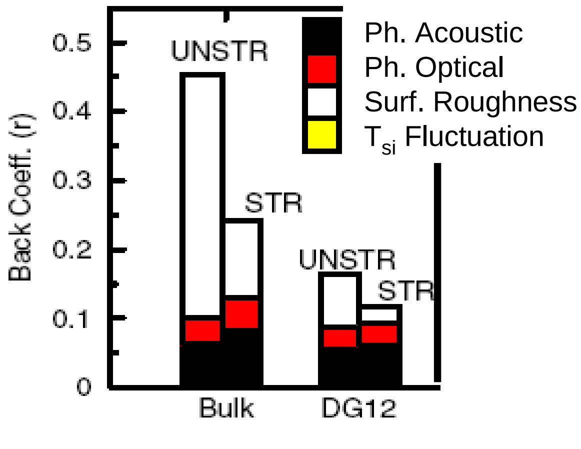
Application to device performance modeling

Strain Silicon : double advantage in QB devices

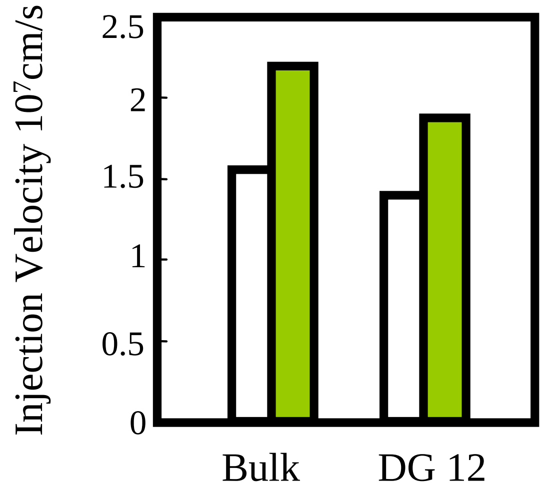
D. Ponton et.al. Proc. Essderc 2006 p. 166

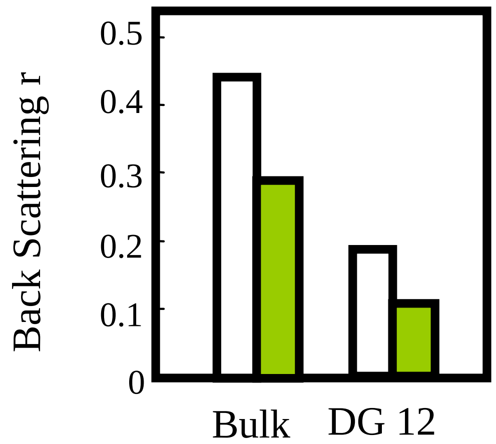
Multi Subband Monte Carlo Simulations





Analytical Model





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

$$\lambda = \frac{1}{2} \times \frac{2\mu_{eff}(E_{eff})\, kT/e}{v_{th}}$$

Limits of Lundstrom's Model

$$r_{HF} = \frac{L_{kT}}{L_{kT} + \lambda}$$

- is only an empirical formula : where does it come from ?
- How to evaluate L_{kT} ? (V(x) is not known)

(In particular the impact of velocity overshoot on V(x), and thus L_{kT} is not self consistently taken into account)

$$\lambda = \frac{2\,kT/e}{v_{th}}\mu$$

- OK in low field
- But in high field rather equal to $\lambda = \alpha \frac{2\,kT/e}{v_{th}}\mu$ with $\alpha \approx \frac{1}{2}$

V_{th} and r_{HF} are valid in non degenerated inversion layers

- How to generalize L_{kT} and λ in degenerated inversion layer ?

(An increase of V_{inj} may also degrade r : is subband engineering a viable strategy ?)

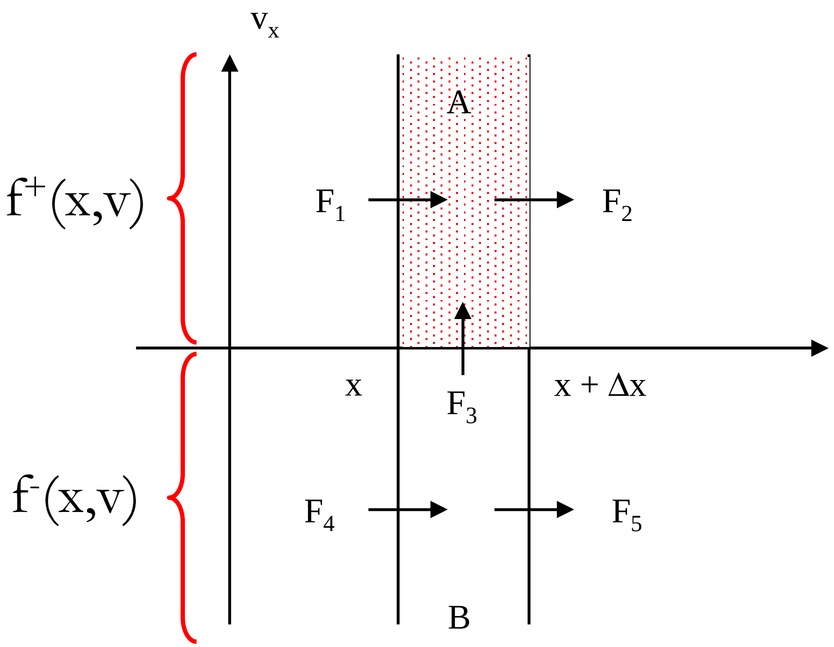
Beyond Lundstrom's Model

R. Clerc, P. Palestri, L. Selmi
« On the Physical Understanding of the kT-Layer Concept in Quasi-Ballistic Regime of Transport in Nanoscale Devices »
IEEE TED 53, p 1634 – 1640 (2006)

1D flux conservation in the relaxation length approximation

1D Balance Equation in the phase space

$$\boxed{F_1 + F_3 = F_2 + C_{A\to B}}$$



$$F_1 = \int_0^\infty f(x,v_x)\, v_x\, dv_x = \Phi^+(x)$$

Collision Integral (**relaxation length approximation**) :

$$C_{A\to B} = \Delta x \int_0^\infty \frac{f(x,v_x) - f_{LE}(x,v_x)}{\lambda / v_x} dv_x = \Delta x \frac{\Phi^+(x) - \Phi^+_{LE}(x)}{\lambda}$$

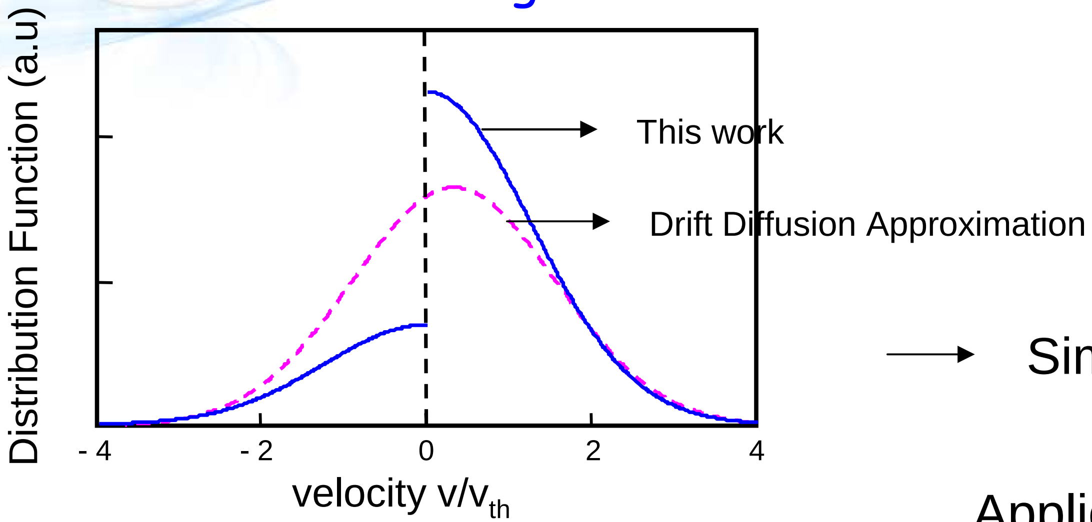
Balance Equation for the flux of carrier along the device

$$\boxed{\frac{d\,\Phi^-}{dx} = -f(x,0^-)\frac{e\,F}{m} - \frac{\Phi^+(x) - \Phi^+_{LE}(x)}{\lambda}}$$

→ Assumption on the shape of $f(x,v_x)$ needed

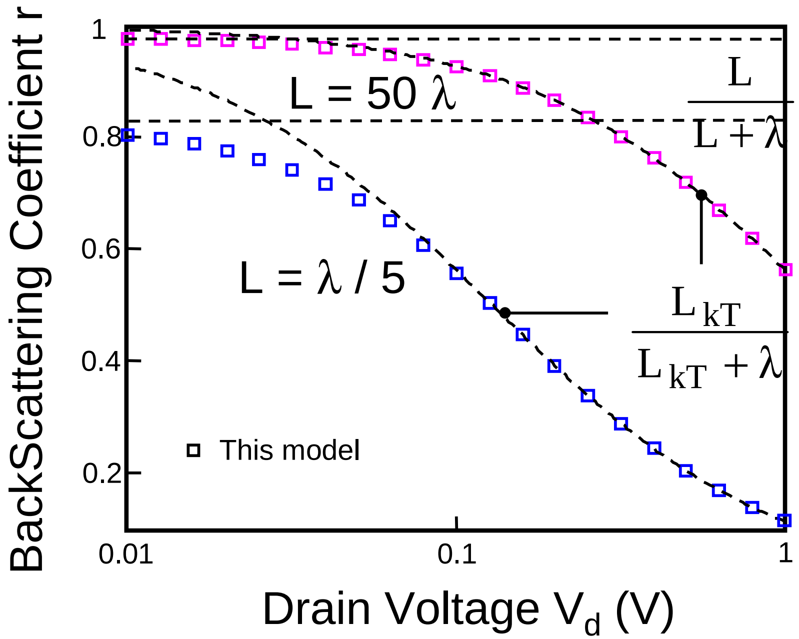
The quasi ballistic Drift Diffusion

Assuming local Maxwellian distribution function (at each point) :



$$f^{\pm}(x,v) = 2\sqrt{\frac{m}{2\pi kT}}\, n^{\pm}(x) \exp\left(-\frac{m v^2}{2kT}\right)$$

$\longrightarrow$ Similar to Drift Diffusion



<u>Application to the backscattering coefficient calculation:</u>

$$r = \frac{L_{kT}(1-\beta)}{\lambda + L_{kT}(1-\beta)}$$

$$\beta = \exp(-L / L_{kT})$$

This equation includes both :

$$r_{LF} = \frac{L}{\lambda + L} \qquad r_{HF} = \frac{L_{kT}}{\lambda + L_{kT}}$$

The quasi ballistic Drift Diffusion

We thus have now a new formalism which includes :

Thermal velocity limitation at the source (Ballistic limit)

Same backscattering coefficient in high and low field (Ballistic mobility)

With no need to calculate LkT …

$\longrightarrow$ An alternative to Drift Diffusion ?

Using this approach, if we derive the current flux :

$$\Phi = q\,(n^{+} - n^{-})\,v_{th} = -\lambda_x v_{th}\frac{d\,n}{dx} - \frac{\lambda_x v_{th}}{kT/q}\,2n^{-}\,F_x$$

Using : $n = n^{+} + n^{-}$

$$\boxed{\Phi = (n^{+} - n^{-})\,v_{th} = -D'\frac{d\,n}{dx} - n\,\mu'\,F_x}$$

$$\boxed{\mu' = \frac{\mu}{1+\mu F_x / v_{th}}}$$

Except for the boundary conditions, it is equivalent to Drift Diffusion, including saturation velocity !

Idem for H. Wang, G. Gildenblat,
"Scattering matrix based compact MOSFET model", in IEDM Tech. Dig., pp. 125–128 (2002)

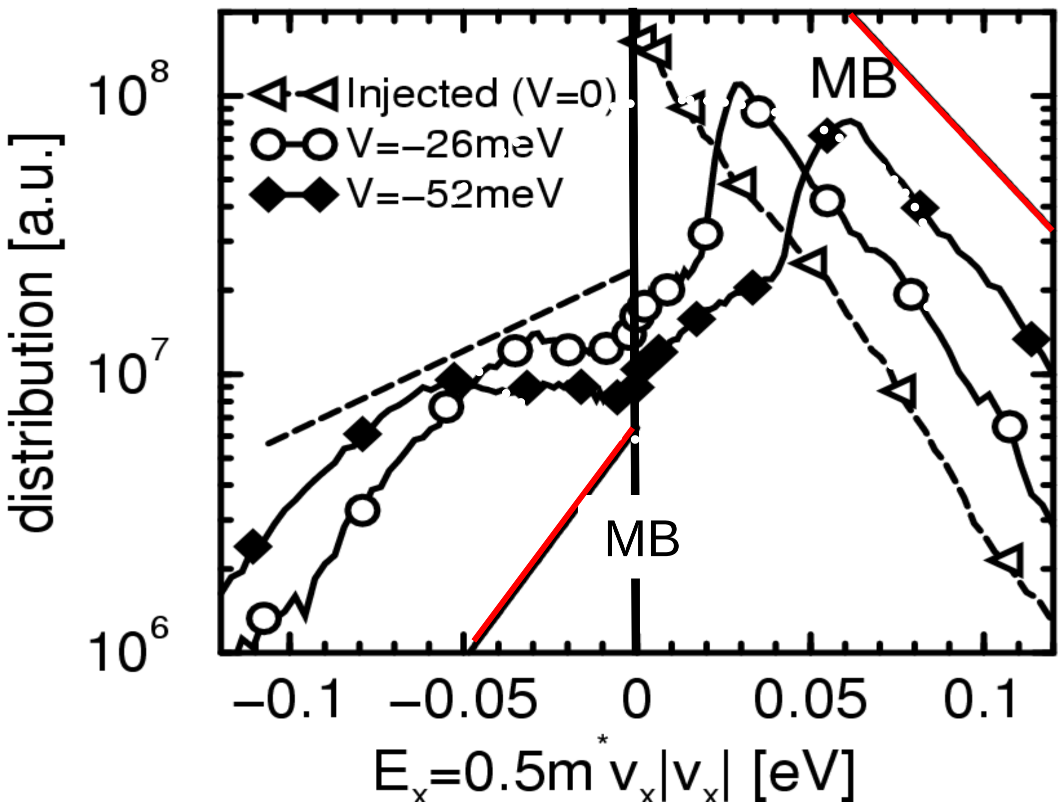
Non Thermal Approach

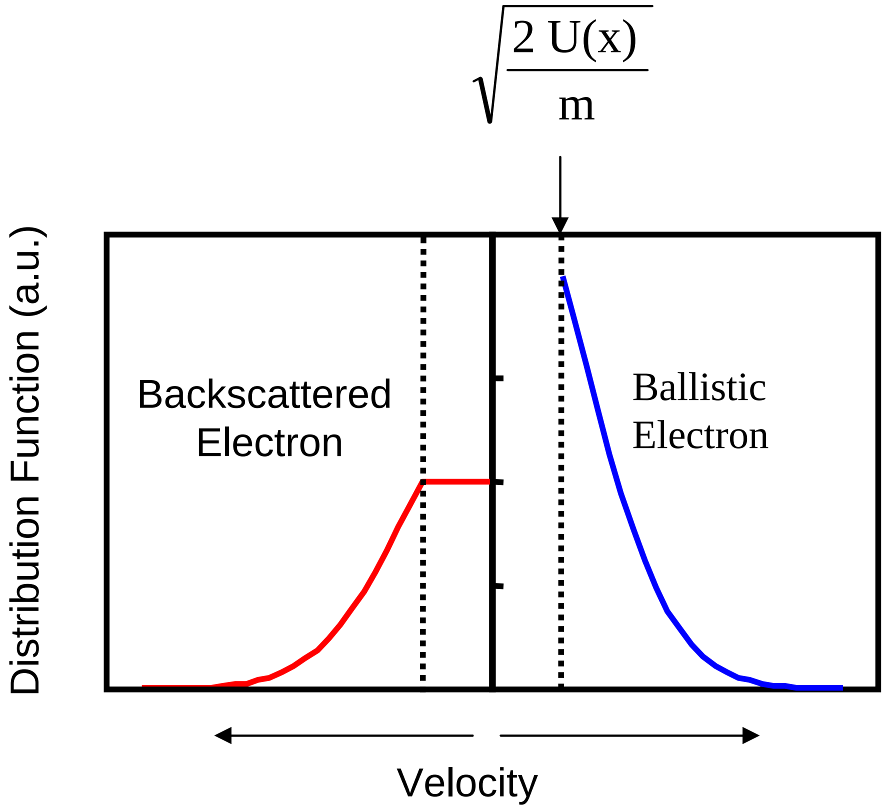
What is wrong with quasi ballistic Drift Diffusion ?

$$\longrightarrow \quad \boxed{f^{\pm}(x,v) = 2\sqrt{\frac{m}{2\pi kT}}\, n^{\pm}(x)\exp\left(-\frac{m\,v^2}{2\,kT}\right)}$$

A more suitable approximated distribution function (at each point) :

From MC simulations

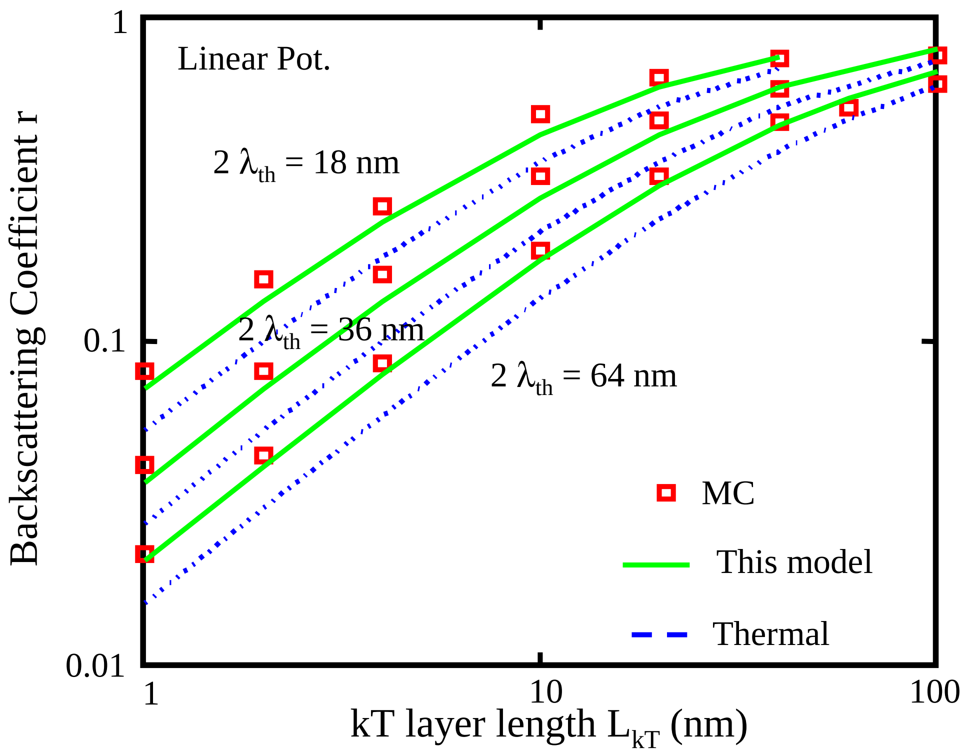


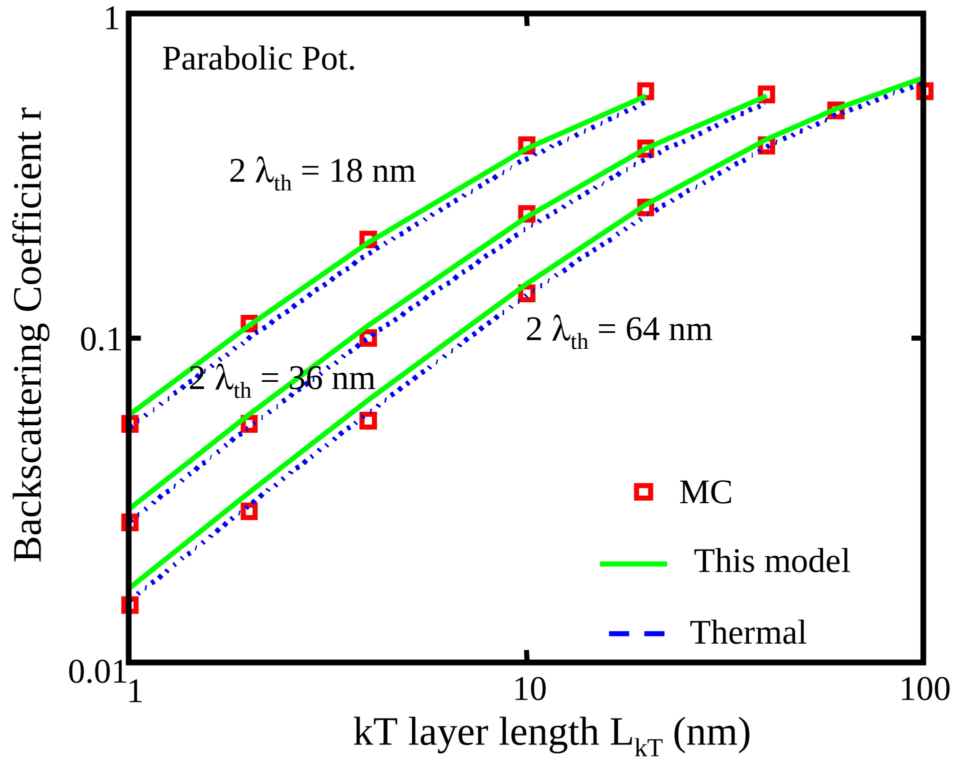


Non Thermal Approach

Backscattering formula :

$$r = \frac{L_{kT}\, A(L_{kT}, L)}{2\lambda + L_{kT}\, A(L_{kT}, L)} \qquad A(L_{kT}, L) = \int_0^{L_{kT}/L} \left[\frac{2\lambda(u)}{2\lambda} \left(1 + \frac{U(u)}{kT}\right) \right]^{-1} du$$

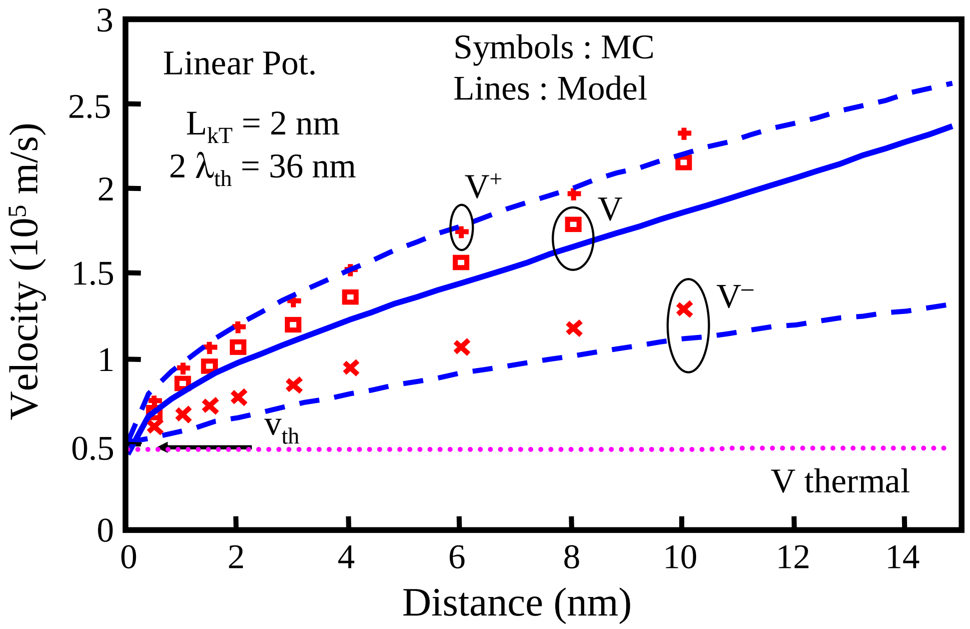




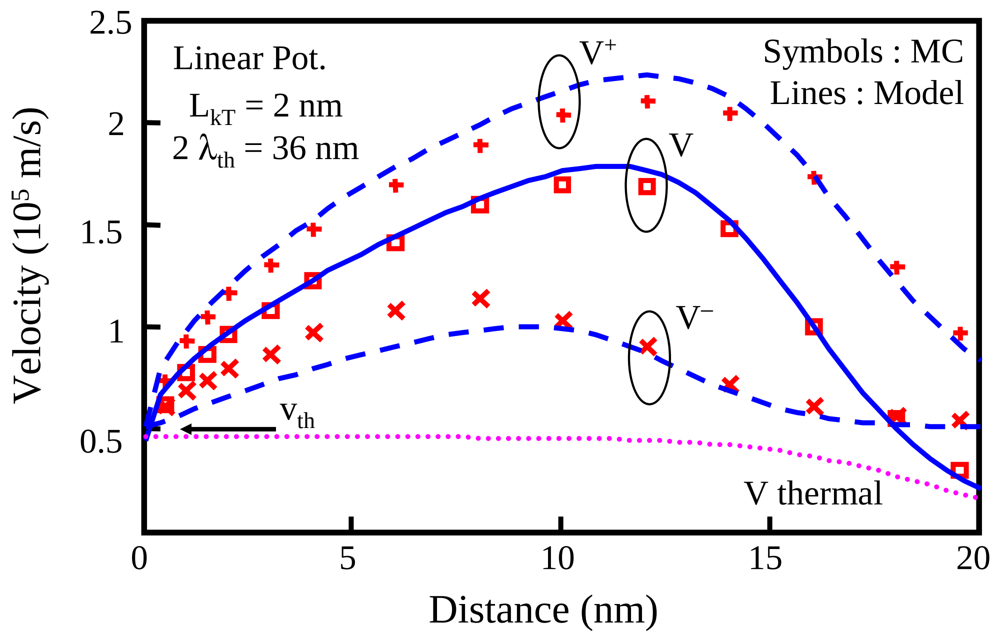
Non Thermal Approach

Velocity profile in high field in a non self consistent linear potential profile

With absorbing drain :



With real drain (emitting) :



Ballisticity extraction from experiments

Ballisticity extraction from experiments

Is there any experimental confirmation of the quasi ballistic nature of transport ?

Not clear yet !

Let us show some results :

- let us consider only the ohmic regime
(more simple : you do not need to know the charge at the virtual source)

- a standard low field mobility extraction has been performed on :

65 like nm Bulk and undoped Fully Depleted SOI technology

featuring physical gate length down to 40 nm

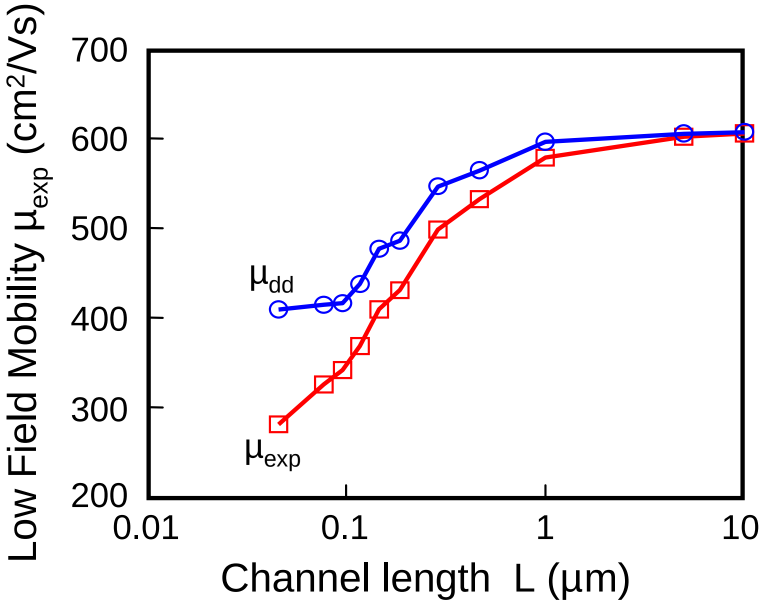
- according quasi ballistic theory :

$$\frac{I_{d\,Lin}}{W} = (1-r)\,\frac{Q_i}{2}\,v_{th}\,\frac{e\,V_d}{kT} = \frac{1}{L}\mu_{app}Q_iV_d \longrightarrow \boxed{\mu_{app} = \frac{L}{L+\lambda}\mu_{dd}}$$

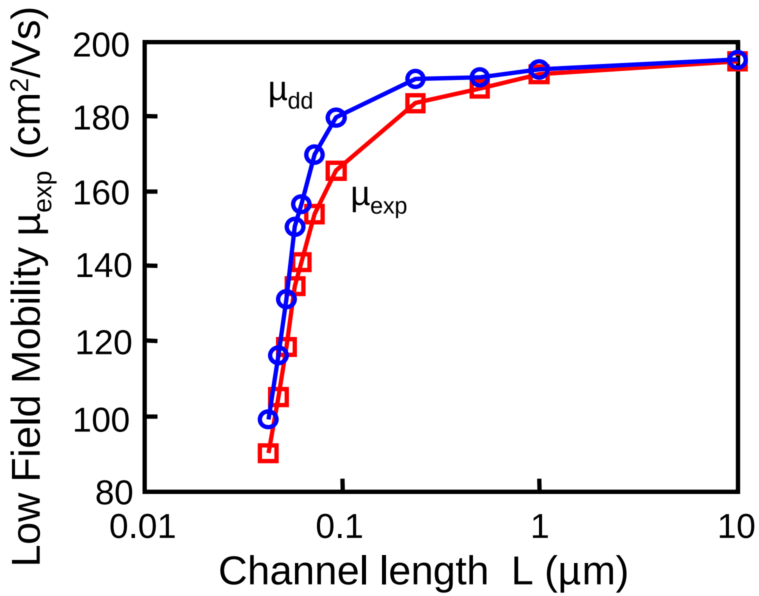
Apparent mobility should decrease with L in the quasi ballistic regime

Ballisticity extraction from experiments

Bulk nMOS



Undoped FD-SOI nMOS



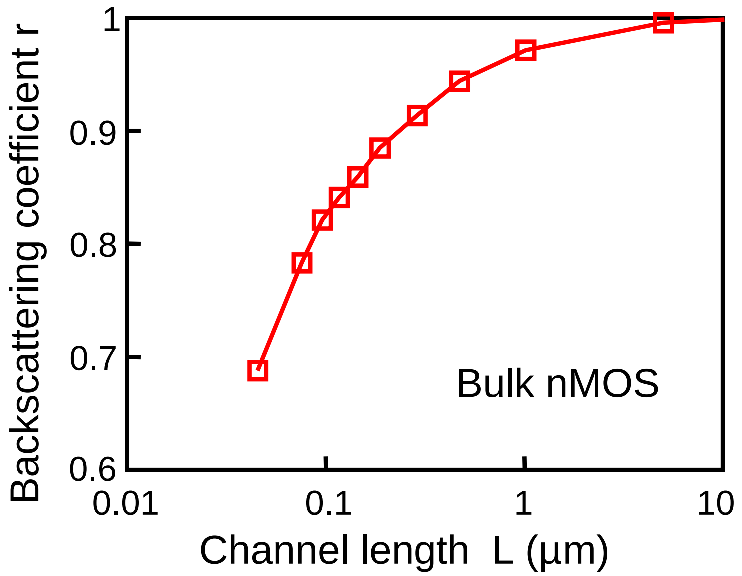
Bulk 65nm CMOS technology
doped channel (≈10^{17}/cm^3) with halos,
SiON gate oxide (CET=2.2nm)
polysilicon gate.

Undoped Fully depleted SOI
Body thickness of 10 nm
Metal gate TiN, 2.5 nm of HfSiON dielectric
Raised source and drain

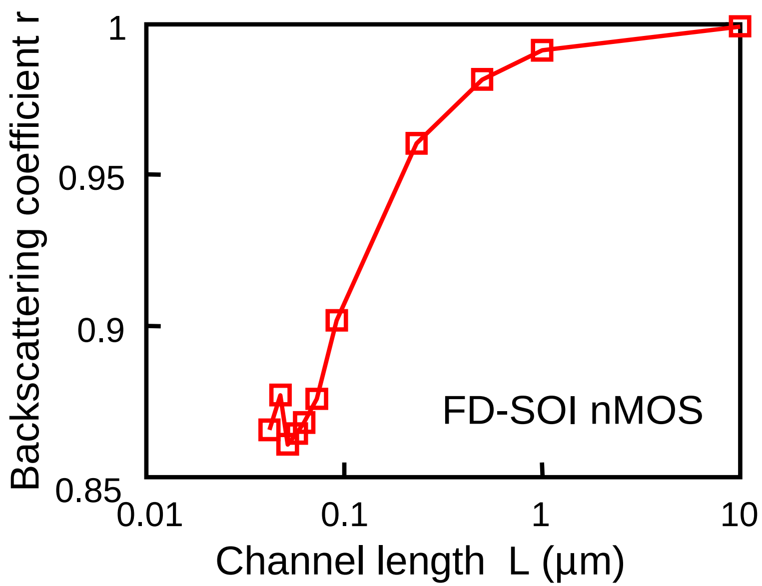
Ballisticity extraction from experiments

The backscattering coefficient has been extracted using $$r = 1 - \frac{\mu_{app}}{\mu_{bal}}$$

Bulk nMOS **r_{LF} ~ 0.7**



Undoped FD-SOI nMOS **r_{LF} ~ 0.85**



Extracted value of r are very large … Neutral defects ?

Conclusions

Conclusions

The Lundstrom backscattering theory provides a powerful guideline
to analyse qualitatively device performance in the quasi ballistic regime

However, It is not a compact model (How to compute LkT ?)

If you try to generalize this approach along the channel
→ quasi ballistic drift diffusion
→ which is similar to drift diffusion with saturation velocity in high field regime

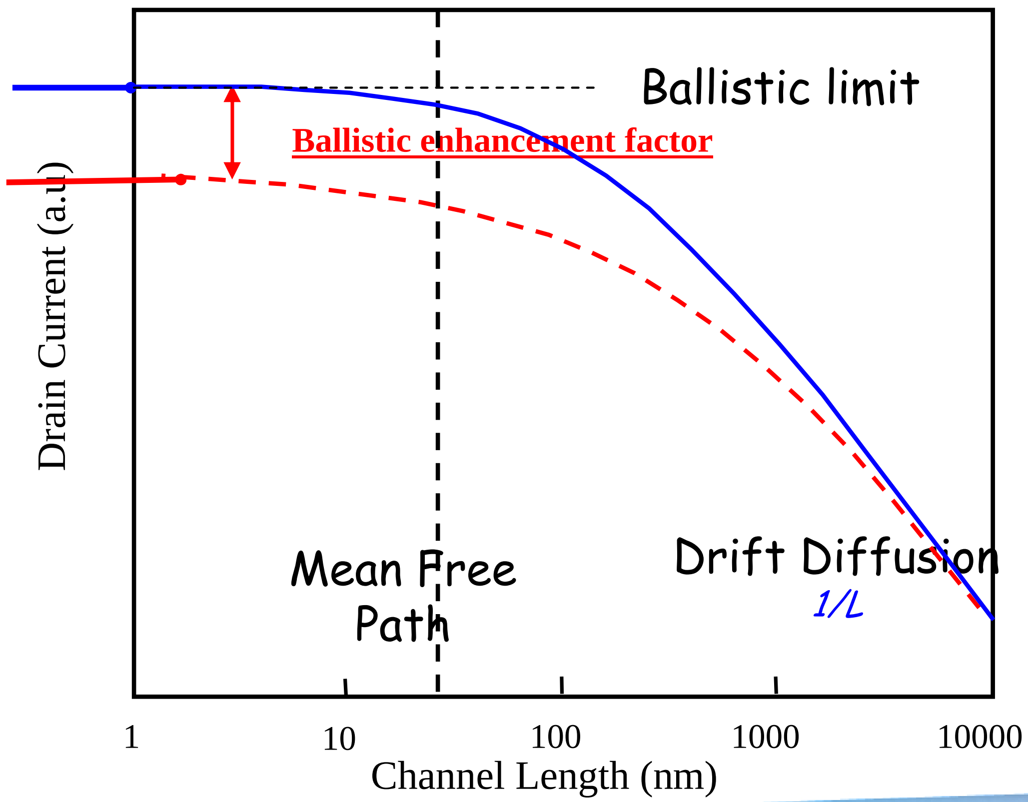
You need to account for the ballistic distribution of carriers

However, experiments shows a more complex picture :
we are not sure yet to operate in the quasi ballistic regime (neutral defects ?)

Thank you for your attention !

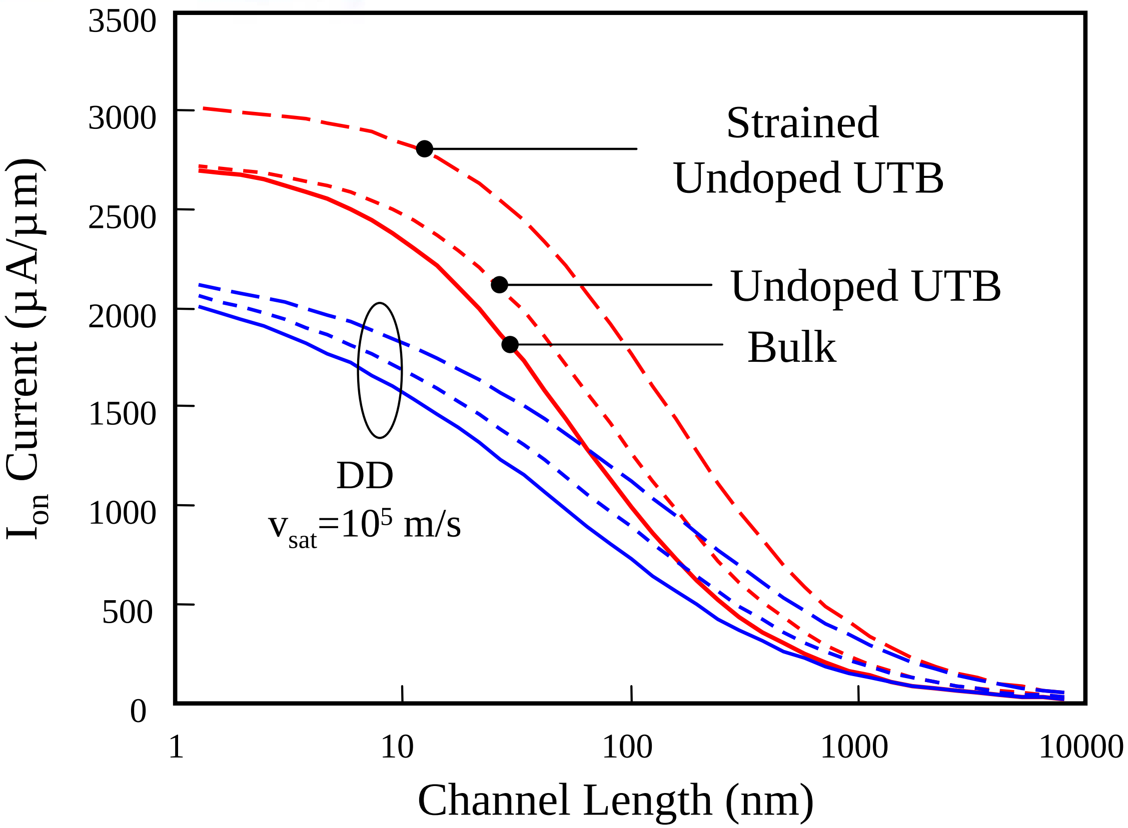
More Exact Quasi Ballistic Model

Drift Diffusion Analytical Model
(Velocity Saturation)



Application to device performance enhancement

Device Optimisation in the Quasi Ballistic Regime



BULK
μ = 130 $cm^2V^{-1}s^{-1}$
V_{inj} = 1.2 × 10^5 m/s
N_{inv} = 1.45×10^{13} cm^{-2}

Undoped UTB
μ = 200 $cm^2V^{-1}s^{-1}$
V_{inj} = 1.2 × 10^5 m/s
N_{inv} = 1.45×10^{13} cm^{-2}

Strained Undoped UTB
μ = 370 $cm^2V^{-1}s^{-1}$
V_{inj} = 1.3 × 10^5 m/s
N_{inv} = 1.45×10^{13} cm^{-2}

2 possible strategies to improve Ion :

- **improving λ**, which mean **improving μ** = effective field mobility

like in pure Drift Diffusion model !

- **improving V_{inj} (subband engineering)**

by DOS reduction

→ Still no clear experimental evidence

Re-investigation of the kT layer Concept

$$r_{HF} = \frac{L_{kT}}{L_{kT} + \lambda}$$ has been derived using Quasi Ballistic Drift Diffusion.

key assumptions on which this formula is based :

- Boltzmann statistics in the contacts
- Non Self consistent potential
- use of the relaxation length approximation with a constant λ

$\longrightarrow$ λ should be energy dependent (especially at high field)

- the population of backscattered carriers (f^-) has an equilibrium Maxwellian distribution :

  at each point x,
  regardless of the channel length
  and of the magnitude of the electric field

$\longrightarrow$ reasonable approximation

Only close to the virtual source
Or along the channel when many collisions are involved