The Nano-Tera Workshop on the Next Generation MOSFET Compact Models

The Roots of the EPFL-EKV Compact Model

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Outline

- Some EKV History
- Explore weak inversion in nano-scale devices
- Extension of EKV to quasi-balistic transport
- Conclusions

A Long History – The Early Days

- Finds its roots in the first models presenting weak inversion published in the 70's
- First charge-based approach taken by Jespers and Memelink (1977)
- Bulk-referenced symmetrical model proposed by Châtelain, but only for strong inversion (1979)
- First model continuous from weak to strong inversion by Oguey and Cserveny (1982), simplified later on by Vittoz for analog design purpose
- Linearization of inversion charge versus surface potential originally proposed by the pioneering work of Maher and Mead (1987)
- First EKV paper describing EKV2 by Enz, Krummenacher and Vittoz (1995)
- First EKV charge-based formulation by Bucher (1997)
- Similar approach by Cunha (1997)
- Inversion charge linearization rediscovered by Gummel and Singhal (2001)
- Rigorous derivation of inversion charge linearization of the EKV by Sallese (2003)

📖 C. Enz, "A Short Story of the EKV MOS Transistor Model," SSCS Newsletter, Vol. 13, No. 3, 2008.

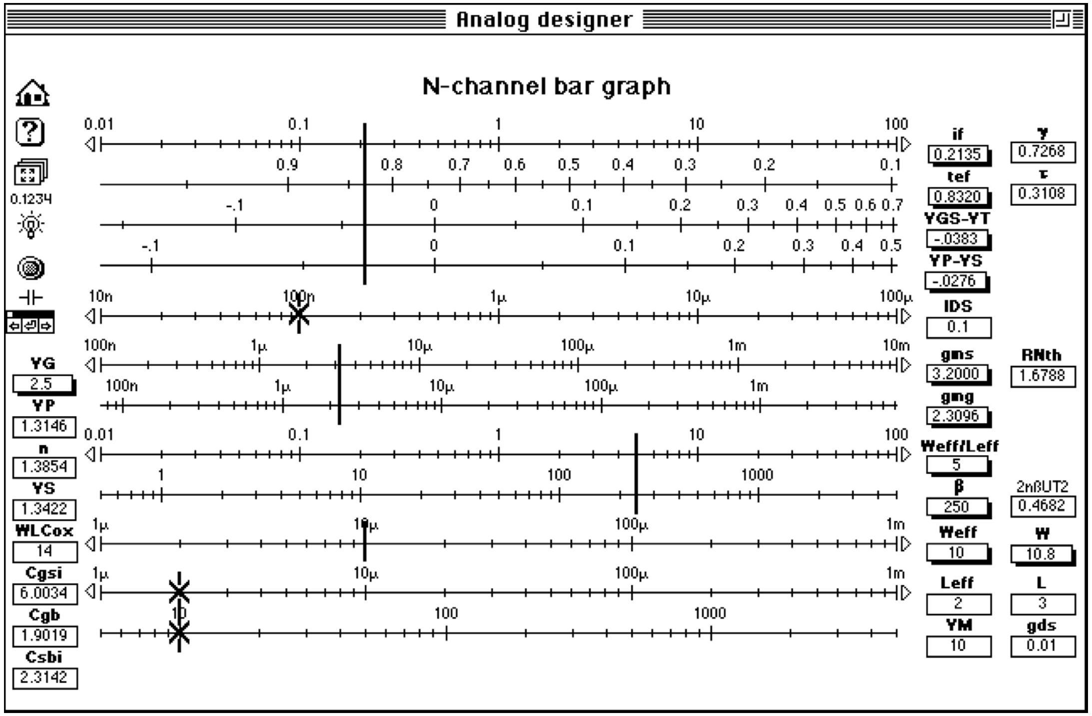
A Long History – The Compact Modeling Stage

- Non-uniform doping was proposed by Lallement (1996)
- EKV compact model 2.6 released in 1997 by M. Bucher
- Implementation in most commercially available circuit simulator by M. Bucher
- Extension of EKV to RF CMOS by Enz (1999)
- Charge-based NQS model added by Sallese and Porret (2000)
- Quantum and polydepletion effects by Lallement (2003)
- Accurate thermal noise model developed by Roy and Enz (2005)
- Selection of EKV3 (Bazigos and Bucher) among 4 other CM by the CMC (2005)
- Accurate flicker noise model added by Enz (2006)
- Publication of the book "Charge-Based MOS Transistor Modeling - The EKV Model for Low-Power and RF IC Design," by Enz and Vittoz (2006)
- Extension of EKV to ballistic/quasi-ballistic transport by Mangla (2011)

📖 C. Enz, "A Short Story of the EKV MOS Transistor Model," SSCS Newsletter, Vol. 13, No. 3, 2008.

The Link between Process and Designers

- EKV is not only a compact model but also a low-power analog-RF **design methodology** based on the **inversion coefficient**
- EKV establishes the link between process and designer



📖 C. Enz, “A Short Story of the EKV MOS Transistor Model,” SSCS Newsletter, Vol. 13, No. 3, 2008.

Why Having Chosen a Charge-based Model?

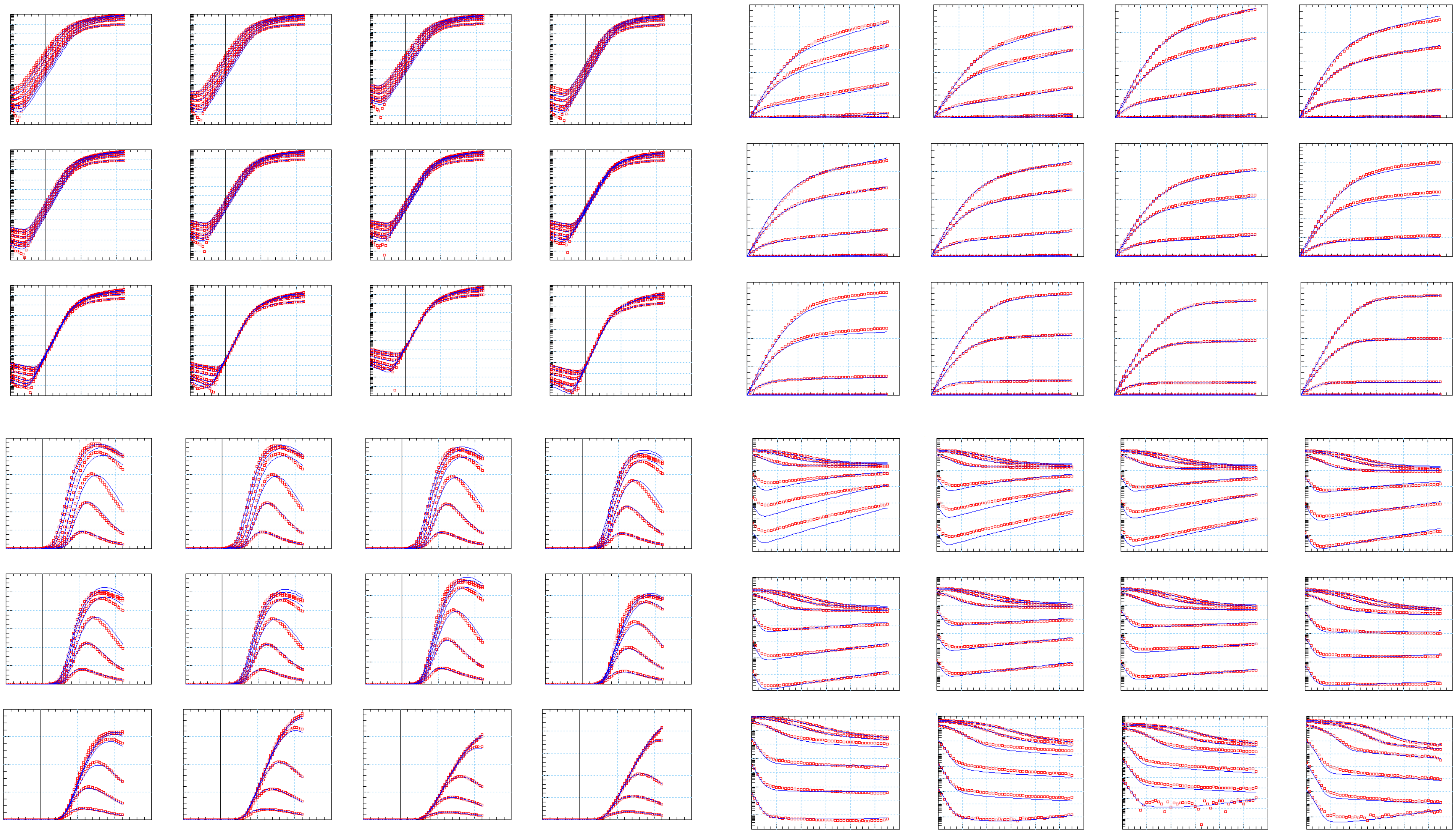
- **Surface-potential** models require **extremely high accuracy** on the surface potential solution, which is not required when solving for inversion charge instead of surface potential
- Take advantage of the direct link existing between **inversion charge** and **transconductances** which remain the most fundamental design parameters
- All most important device characteristics can be expressed in terms of **source** and **drain inversion charges**
- Ensure **charge conservation** and hence avoid any voltage drift when simulating charge-based circuits such as SC

What's Next? – UCB-EPFL Collaboration

The UCB-BSIM and EPFL-EKV groups have agreed to collaborate on the long-term development and support of BSIM6 as an open-source MOSFET SPICE model for worldwide use.

This is an exciting opportunity to leverage the long history and large user base of the BSIM model with the long experience and active role of EKV in furthering charge-based compact model.

BSIM6 – Extraction on 40nm Process with beta2



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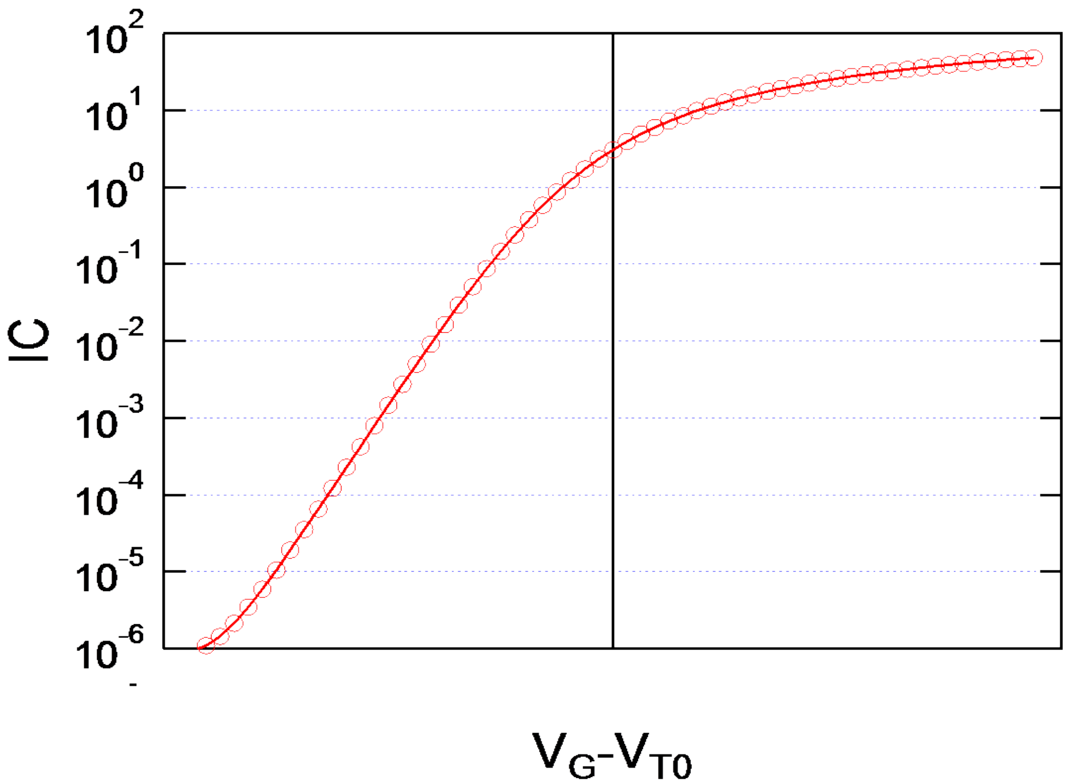
Weak Inversion in Nano-scale MOSFETs

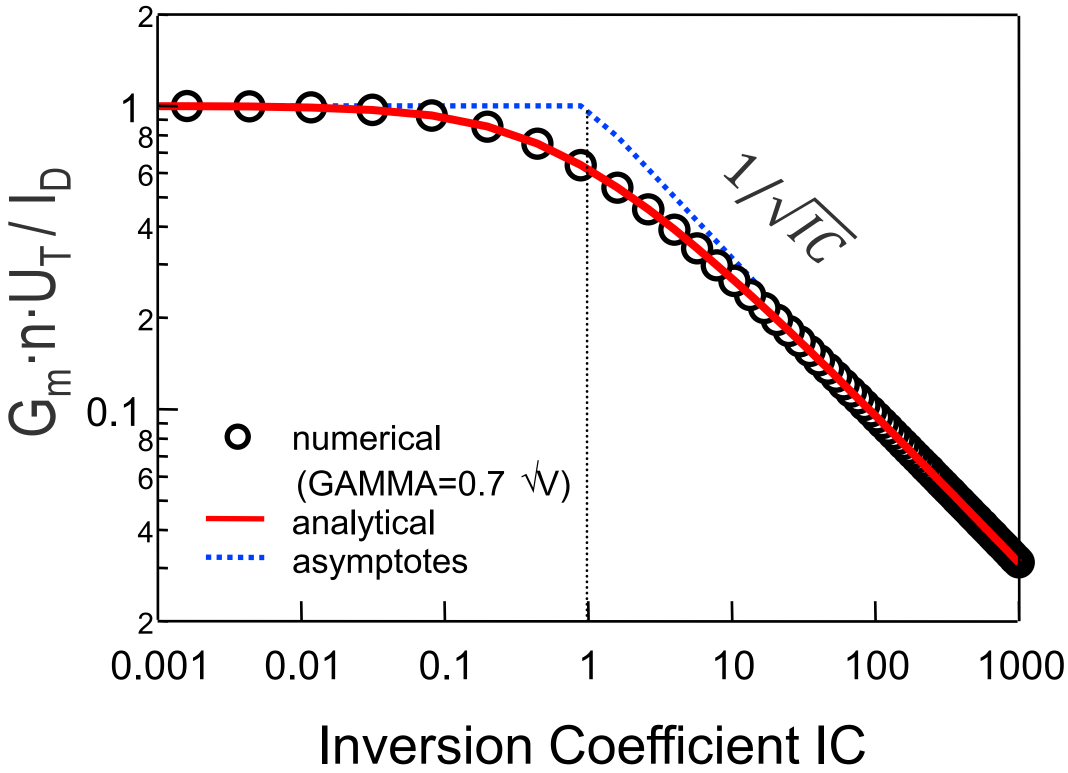


- Weak inversion spans over more than 5 decades of current whereas strong inversion hardly represents 2 decades

Weak Inversion in Nano-scale MOSFETs

- The device performance in strong inversion is strongly limited by short-channel effects such as velocity saturation
  - Current becomes linear with gate voltage
  - Transconductance ultimately limited by saturated velocity
  - Current and transconductance become independent of gate length
  - Transit frequency only scales as $1/L$ instead of $1/L^2$
- In weak inversion the longitudinal field remains smaller than the critical field and hence the transistor should be less impacted by velocity saturation
  - Current remains exponential with gate voltage
  - Transconductance remains proportional to current
  - Current and transconductance continue to scale as $1/L$
  - Transit frequency scales as $1/L^2$ taking full advantage of down-scaling
  - Current strongly affected by DIBL
  - Resulting in degraded output resistance and intrinsic gain

Current Efficiency – The Long-channel G_m / I_D



$$IC \triangleq \frac{I_D}{I_{spec}} \quad \text{(saturation)}$$

$$I_{spec} \triangleq 2n \cdot \beta \cdot U_T^2$$

$$\beta \triangleq \mu \cdot C_{ox} \cdot \frac{W}{L}$$

- The current efficiency is maximum in weak inversion (WI for IC<0.1)
- It decreases like $1/\sqrt{IC}$ in strong inversion (SI for 10<IC)

Effect of Velocity Saturation (VS) on the Current in SI

- Assuming a piecewise linear velocity-field function, the current in SI and saturation, neglecting the effect of mobility reduction due to the vertical field, is given by

$$i_d = \frac{2q_s^2}{1+\sqrt{1+(\lambda_c \cdot q_s)^2}} \quad \text{with} \quad q_s \triangleq \frac{Q_i(0)}{Q_{spec}} \cong \frac{V_P - V_S}{2U_T} \quad \text{with} \quad \begin{aligned} I_{spec} &\triangleq 2n\beta U_T^2 \\ Q_{spec} &\triangleq -2nC_{ox}U_T \end{aligned}$$

  - Velocity saturation parameter

$$\lambda_c \triangleq \frac{2\mu_0 \cdot U_T}{v_{sat} \cdot L} = \frac{2U_T}{E_c \cdot L}$$

  - For very short channel and/or high overdrive voltage

$$\lambda_c \cdot q_s = \frac{\mu_0}{v_{sat}} \cdot \frac{V_P - V_S}{L} \gg 1 \quad \Rightarrow \quad i_d \cong \frac{2q_s}{\lambda_c}$$

  or in denormalized units

$$I_D \cong W \cdot n \cdot C_{ox} \cdot v_{sat} \cdot (V_P - V_S) = W \cdot C_{ox} \cdot v_{sat} \cdot (V_G - V_{T0} - n \cdot V_S)$$

  - The current becomes a **linear function** of the charge and therefore of the overdrive voltage and also **independent of the length**

Effect of VS on the Transconductance in SI

- The effect of VS on the source transconductance is given by

$$g_{ms} \triangleq \frac{G_{ms}}{G_{spec}} = \frac{q_s}{\sqrt{1+(\lambda_c \cdot q_s)^2}} \quad \text{with} \quad G_{spec} \triangleq \frac{I_{spec}}{U_T} = 2n\beta U_T$$

- For $\lambda_c >> 1$, g_{ms} reduces to $1/\lambda_c$ or in denormalized form

$$G_{ms} \cong \frac{G_{spec}}{\lambda_c} = n \cdot W \cdot C_{ox} \cdot v_{sat}$$

- G_{ms} becomes **independent of the length and of the current**
- The G_m / I_D becomes

$$\frac{g_{ms}}{i_d} \triangleq \frac{G_{ms} \cdot U_T}{I_D} = \frac{\lambda_c^2 \cdot q_s / 2}{1+(\lambda_c \cdot q_s)^2 - \sqrt{1+(\lambda_c \cdot q_s)^2}} \cong \frac{1}{2q_s} = \frac{1}{\lambda_c \cdot i_d}$$

- G_m / I_D decreases **inversely proportional to i_d** instead of $\sqrt{i_d}$

Effect of VS on the Current in WI

- Velocity saturation also affects the current in weak inversion (WI) in saturation

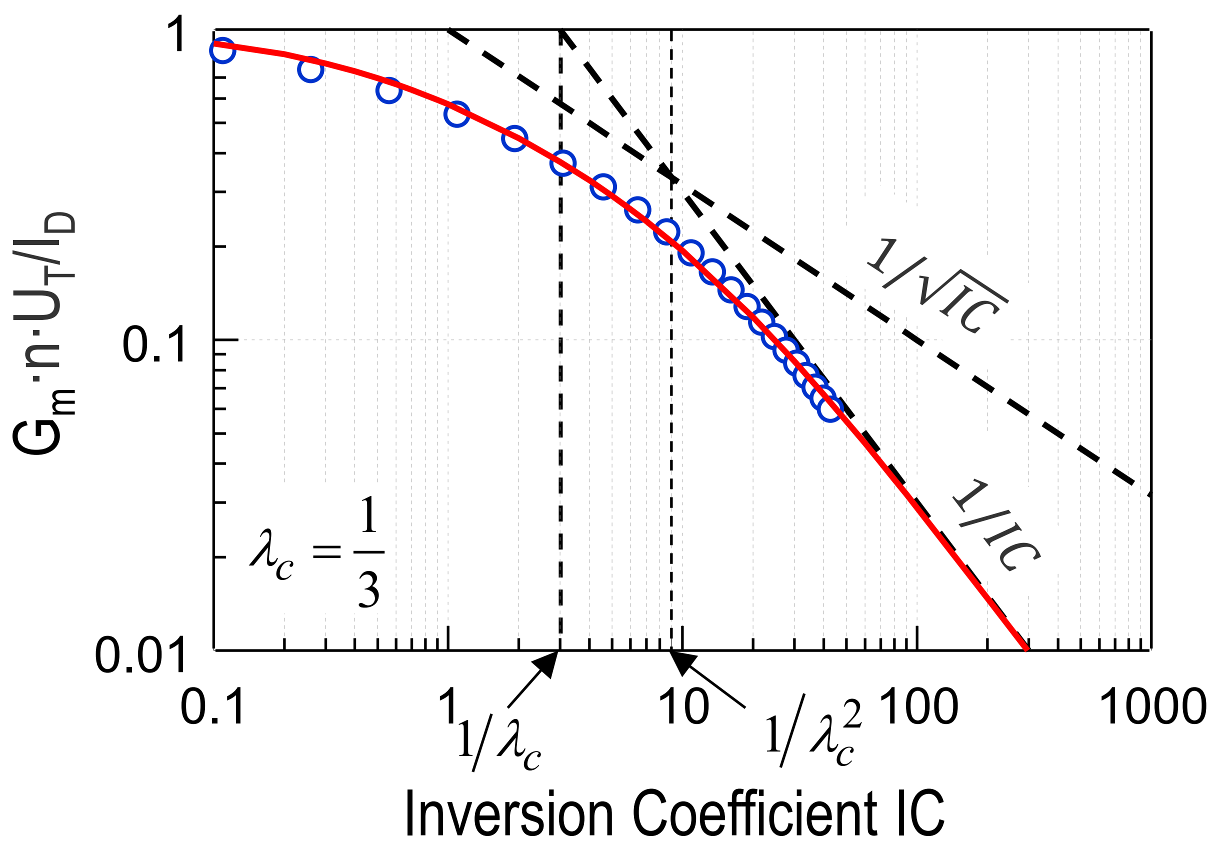
$$i_d \triangleq \frac{I_D}{I_{spec}} = \frac{q_s}{1+\lambda_c/2}$$

- The normalized source transconductance is then given by

$$g_{ms} \triangleq \frac{G_{ms}}{G_{spec}} = \frac{q_s}{1+\lambda_c/2} = i_d$$

- The G_{ms}/I_D ratio is **not affected by velocity saturation** and remains equal to unity as for the long channel case

Current Efficiency – Short-channel G_m / I_D

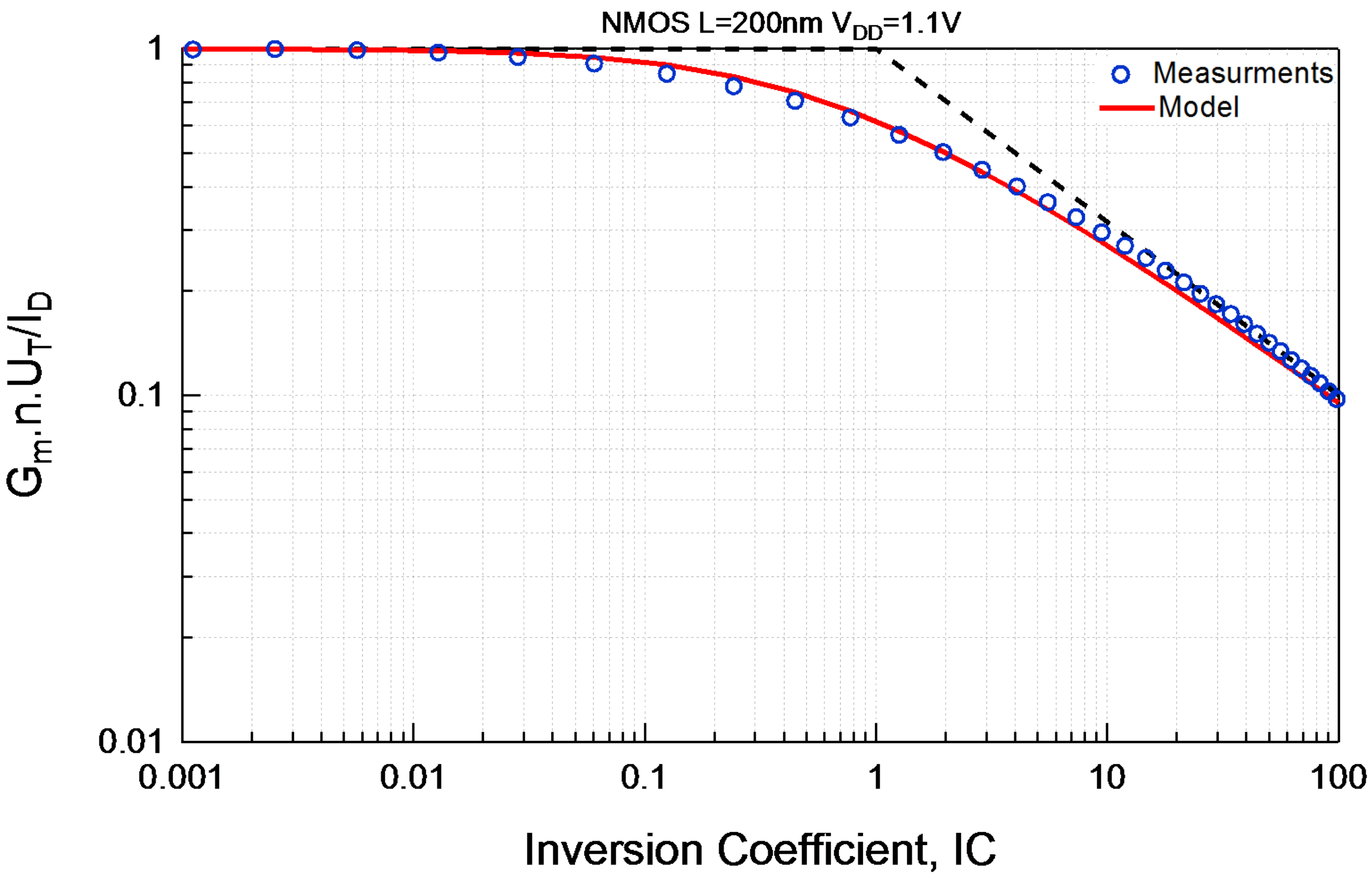


$$\lambda_c \triangleq \frac{2\mu_0 \cdot U_T}{v_{sat} \cdot L} = \frac{2U_T}{E_c \cdot L}$$

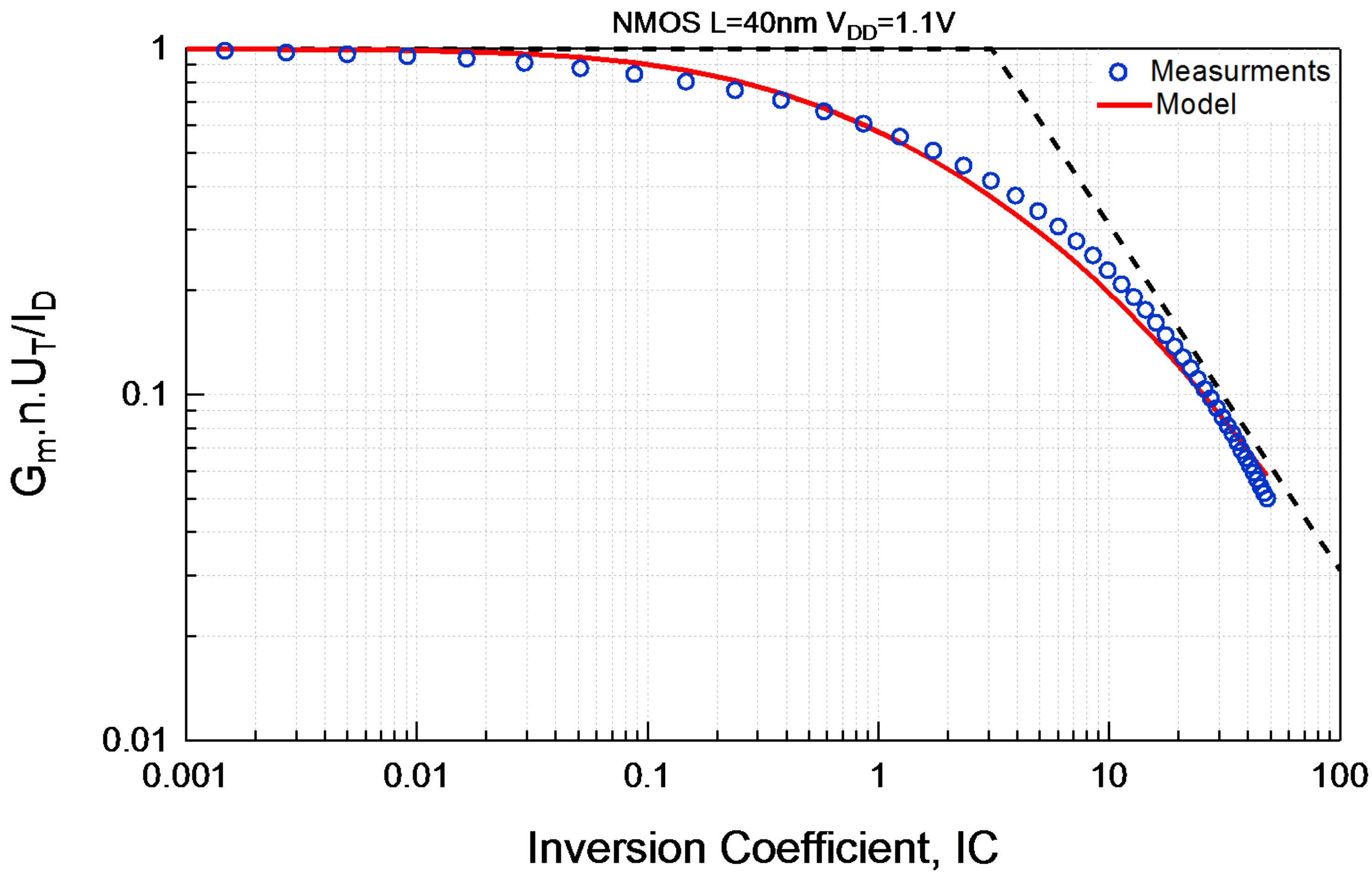
- Velocity saturation strongly degrades current efficiency in strong inversion (IC > 10)

A. Mangla, J.-M. Sallese and C. Enz, MIXDES 2011

G_m / I_D Measured on 40nm Bulk CMOS Process – Long



G_m / I_D Measured on 40nm Bulk CMOS Process – Short

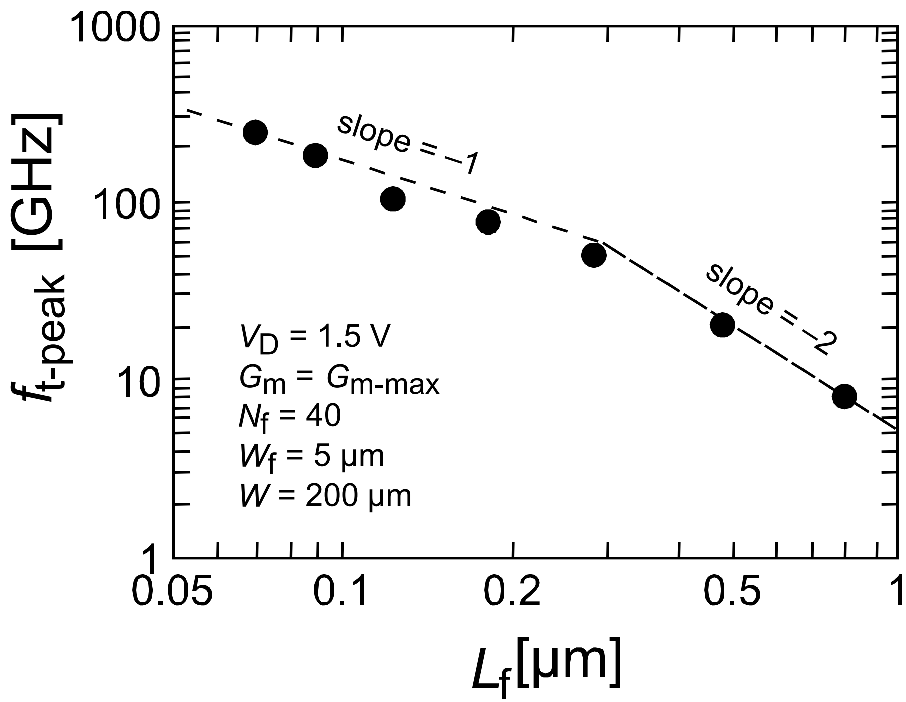


Transit Frequency Scaling

- Scaling of ω_t is affected by short-channel effects such as **velocity saturation**

$$\left.\begin{array}{r} G_{msat} \cong W \cdot C_{ox} \cdot v_{sat} \\ C_G \propto W \cdot L_f \cdot C_{ox} \end{array}\right\} \rightarrow \omega_t \triangleq \frac{G_{msat}}{C_G} \propto \frac{v_{sat}}{L_f}$$

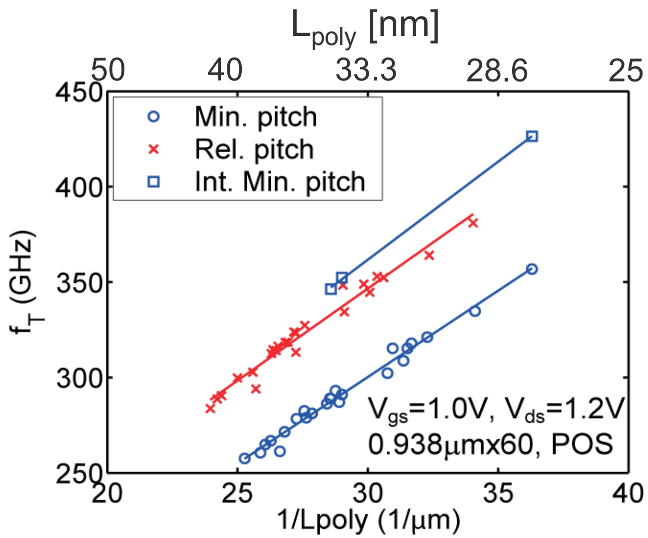
- Scales only as $1/L_f$ instead of $1/L_f^2$ when velocity saturation is present

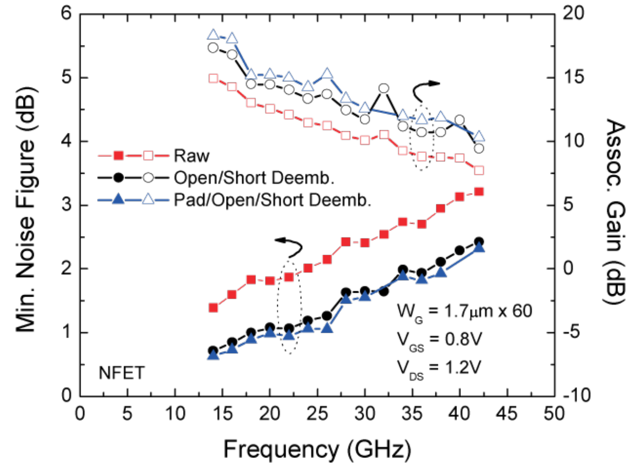


H. S. Momose et al., IEDM 1996.

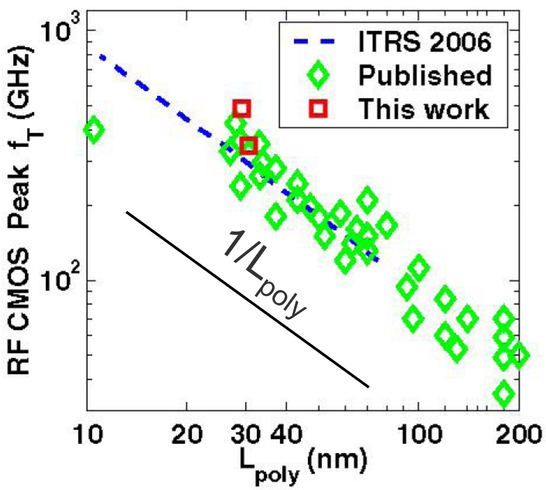
FoM of a 45 nm CMOS Process

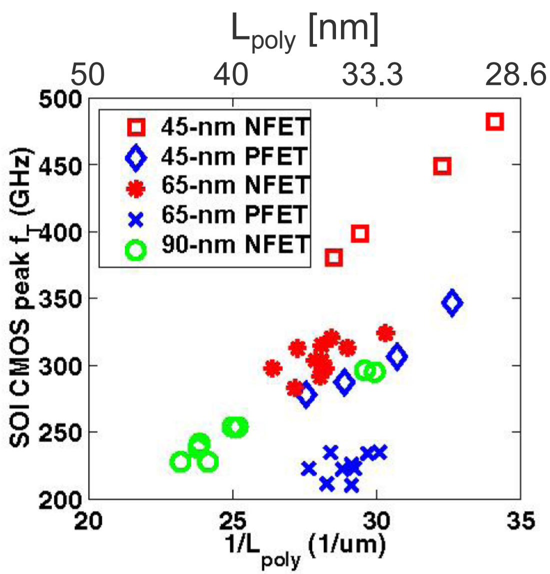
Bulk





SOI





Hongmei Li, *et al.*, VLSI Symposium 2007

Sungjae Lee, *et al.*, IEDM 2007

Frequency Limitations – 65 nm Process

- Transit frequency estimation for a n-channel transistor with standard V_T

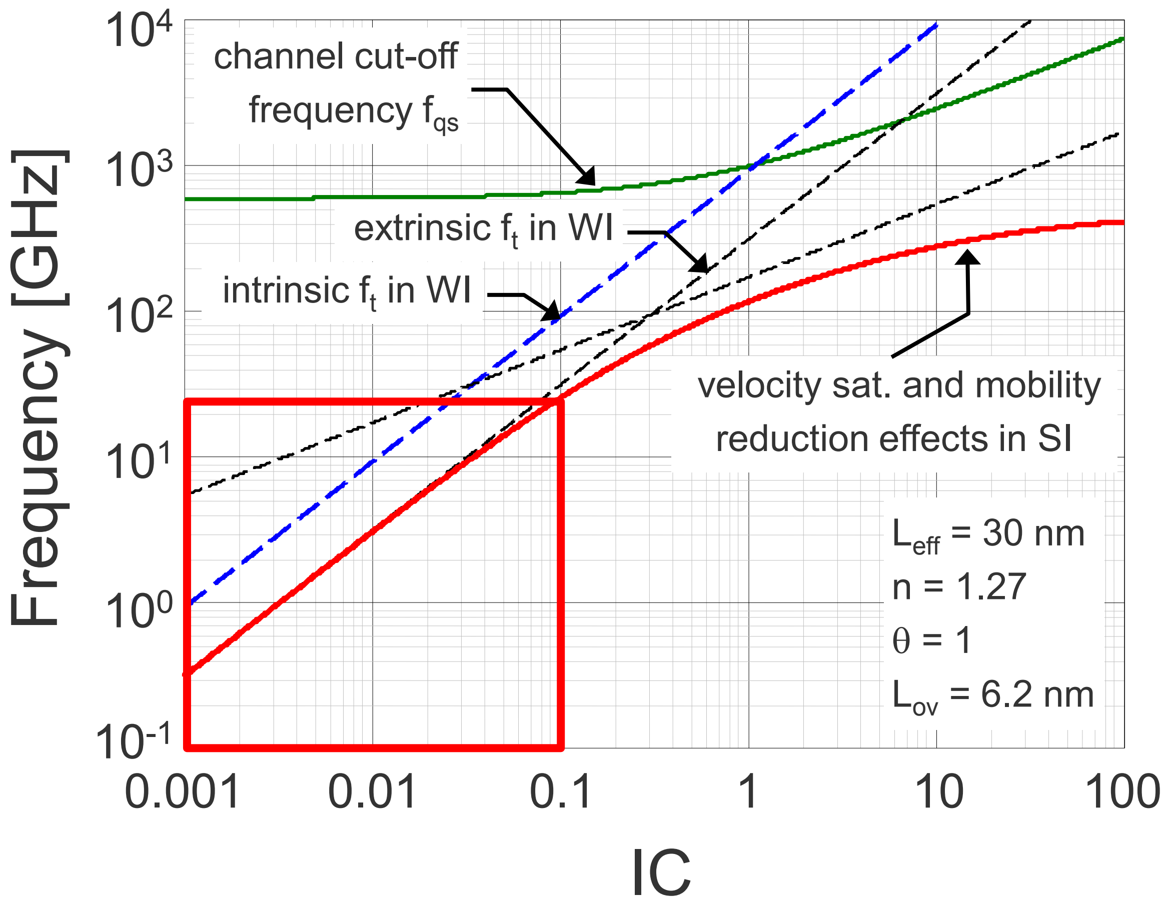
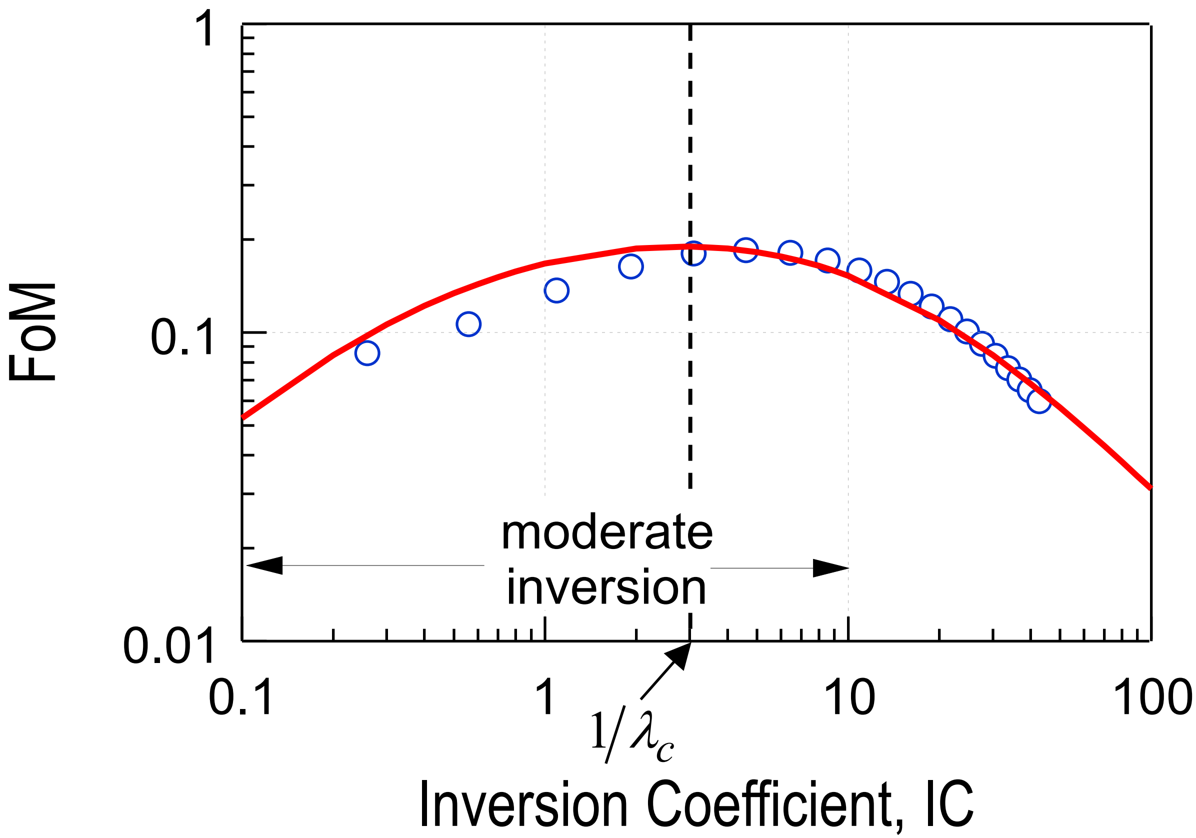


Figure-of-Merit for Low Power RF Design



$$FoM \triangleq \frac{g_{ms} f_t}{i_d} \propto \begin{cases} i_d & \text{WI} \\ \frac{1}{i_d} & SI \end{cases}$$

$$\lambda_c \triangleq \frac{2\mu_0 \cdot U_T}{v_{sat} \cdot L} = \frac{2U_T}{E_c \cdot L}$$

- Moderate inversion is a good trade-off for having at the same time high current efficiency and maximum gain at RF for a given current

A. Shameli and P. Heydari, *ISLPED* 2006
T. Taris, *et al.*, RFIC 2011
A. Mangla, J.-M. Sallese and C. Enz, MIXDES 2011

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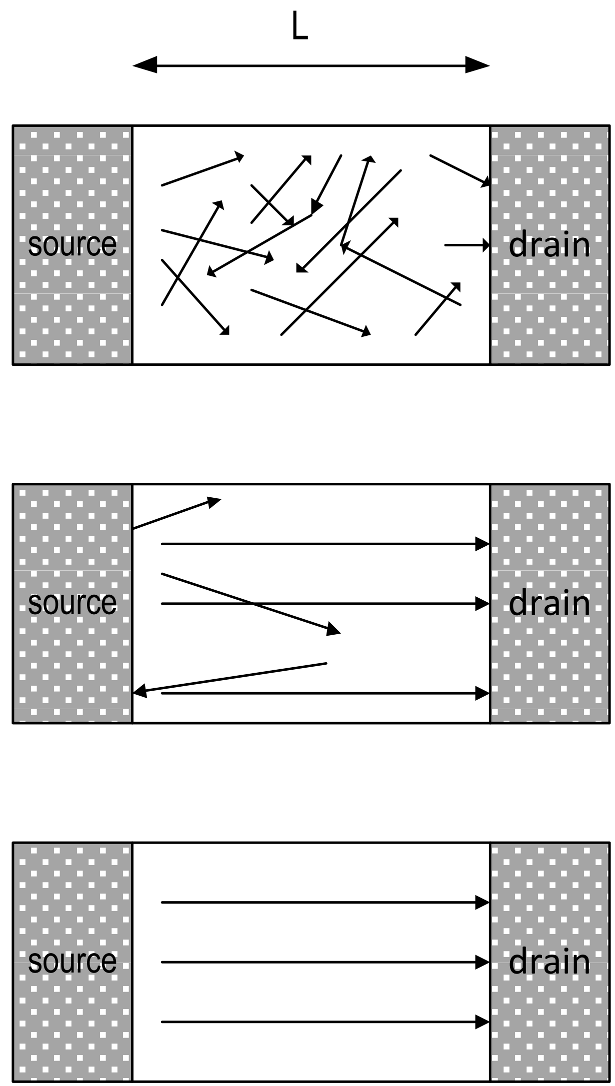
Carrier Transport Mechanisms in MOSFETs

- L >> λ (carrier mean-free-path)
  - Diffusive transport (drift and diffusion)
  - Collision dominated
  - Well described by conventional mobility theory
- L ~ λ
  - Quasi-Ballistic transport where carriers encounter limited amount of scattering from source and drain
  - Mobility theory no longer describes transport
- L < λ
  - Ballistic transport
  - Collision free
  - Controlled by carrier injection from source into the channel



K. Natori, "Ballistic/quasi-ballistic transport in nanoscale transistor," *Applied Surface Science*, Jul. 2008.

Scalable Models from Ballistic to Drift-Diffusion

- The classical approach to Ballistic modeling is quite simple
- However, it is not seamlessly scalable
- It cannot be directly scaled up to result in the conventional drift-diffusion model
- Designers would need to use different models for short and long channel devices at the same technology node
- It is apparent then that we need a compact model that either
  - **Extends the ballistic model** to include the drift-diffusion model, or
  - **Extends the drift-diffusion model** to include the ballistic case.

EKV Continuous Model

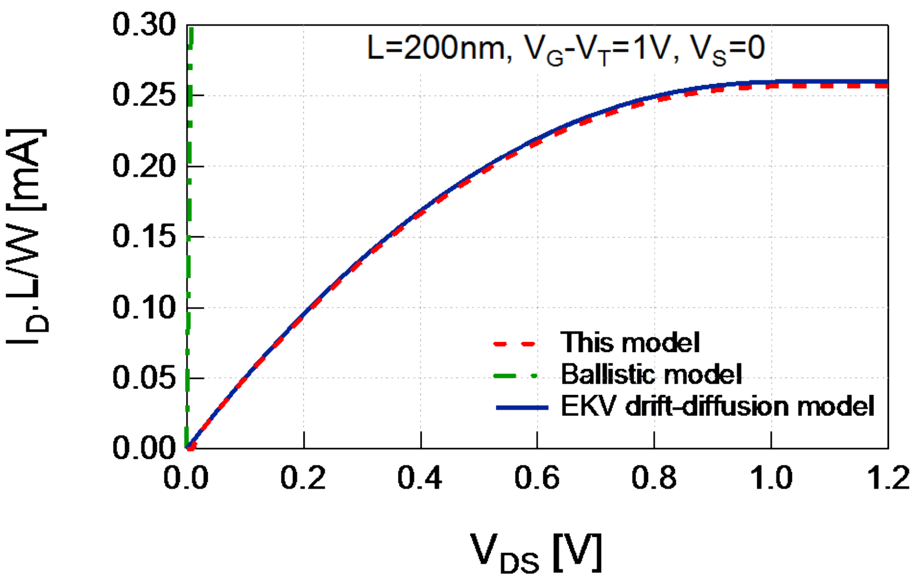
- The classical DD EKV model has been extended to include **ballistic transport**
- The electrostatic is identical to the classical EKV model
- The ballistic behavior is added following **a similar approach to Mugnaini**, but with a simpler implementation
- Still early work and requires additional improvement and validation
- The characteristics of our continuous model at various channel lengths is shown, and the results are compared with the Ballistic (B) model and Drift-Diffusion (DD) model (without velocity saturation)

G. Mugnaini and G. Iannaccone, "Physics-Based Compact Model of Nanoscale MOSFETs—Part I: Transition From Drift-Diffusion to Ballistic Transport," *IEEE Transactions on Electron Devices*, Aug. 2005

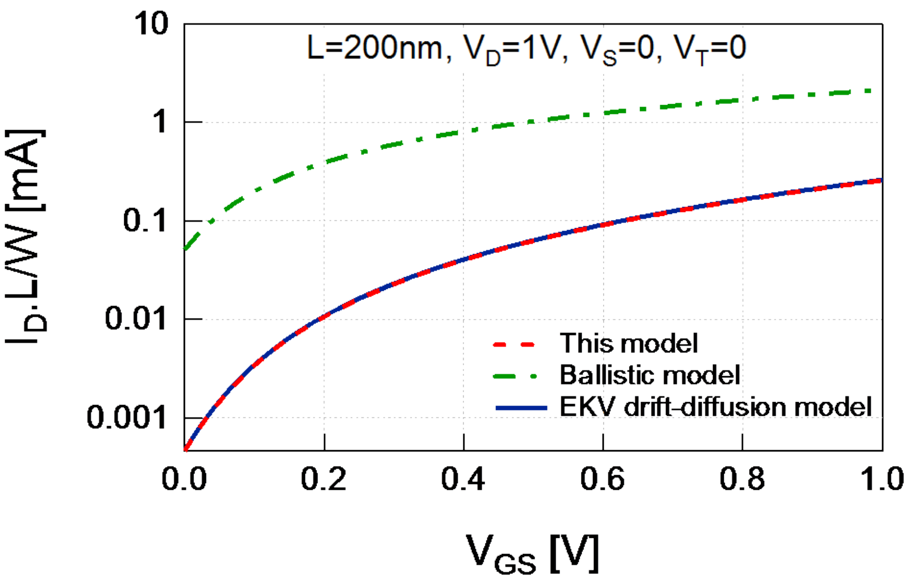
Behavior of a Continuous Model – Long Channel

- For long-channel devices (L=200nm), the model follows the DD model

Output Characteristics



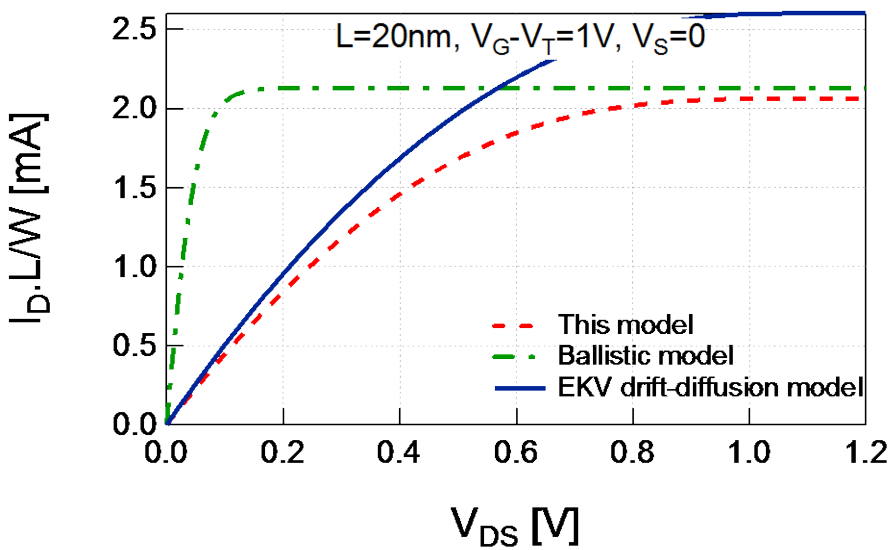
Transfer Characteristics



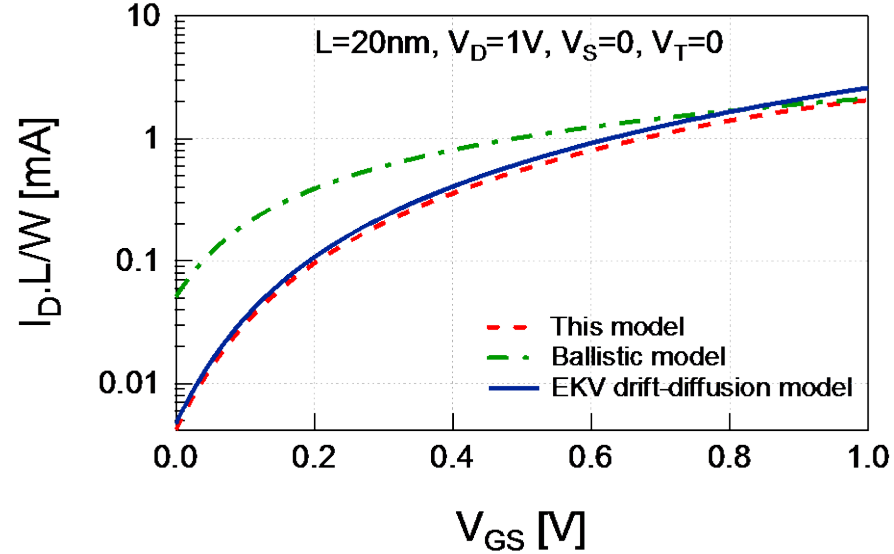
Behavior of a Continuous Model – Short Channel

- For short-channel devices (L=20nm), the model operates as quasi-ballistic, it follows the DD model at low bias and switches to B at higher bias

Output Characteristics



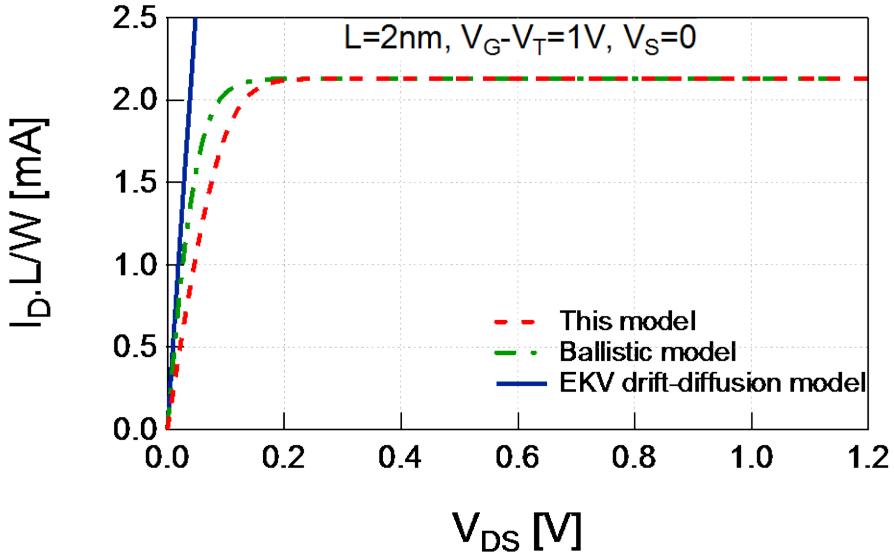
Transfer Characteristics



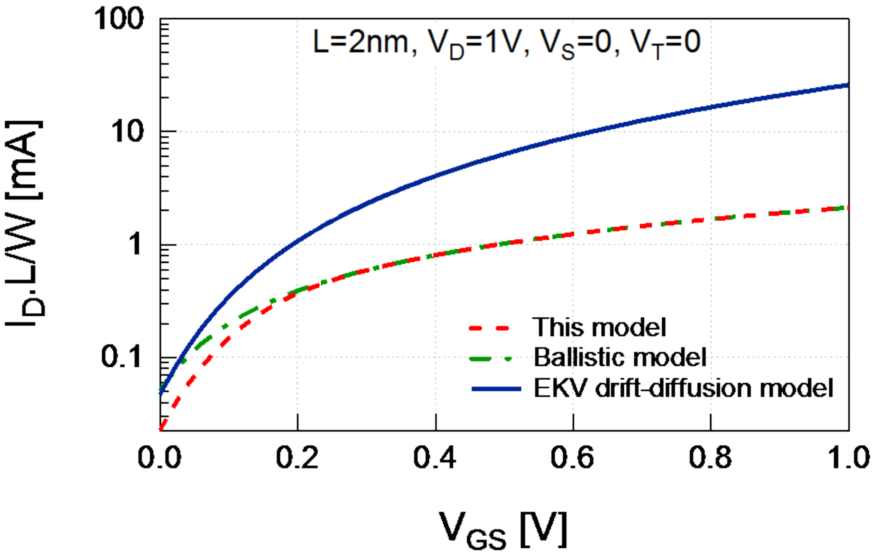
Behavior of a Continuous Model – Very Short Channel

- For very short devices (L=2nm), the model mostly follows the ballistic model

Output Characteristics



Transfer Characteristics



Conclusion

- BSIM and EKV have teamed up to work on the development of the new BSIM6 bulk MOSFET model
- Early extraction results on 40nm process show excellent scalability and good behavior
- Technology and voltage scaling pushes operating points more and more into weak inversion
- Velocity saturation strongly affects the current in strong inversion and also in moderate inversion but not much in weak inversion
- Current efficiency strongly degraded in strong inversion but still optimum in weak inversion
- First results on scalable EKV compact model which includes quasi-ballistic transport look promising