A new Analytical Model of Channel Hot Electron (CHE) and CHannle Initiated Secondary Electron (CHISEL) Current Suitable for Compact Modeling

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Introduction

- Hot carrier phenomena are important because
  - CHE current affects negatively the MOS reliability (interface states and charge trapping in the oxide)
  - CHE injection is the most used mechanism to program Flash memories
  - CHISEL injection has been recently introduced to improve Flash memory program efficiency
- CHISEL current simulations require Monte-Carlo calculations, thus discouraging their frequent use
- In this scenario, the aim of this work is to develop an analytical model of CHE and CHISEL current, which can be included in Spice models of MOS and Flash memories

Basics of the model

- This model is designed to be included in Spice-like models of MOS and Floating Gate (FG) devices
- Hence, we know the drain-source current I_{DS} and the saturation voltage V_{SAT} directly from Spice models
- For a correct modeling of hot-carriers phenomena, the field in the channel has to be accurately estimated: the peak of the lateral field, E_M, and the length of the pinch-off region ΔL_E are given by

$$E_M = \frac{V_{DS} - V_{SAT}}{\Delta L_E}$$

$$\Delta L_E = 0.21 \cdot x_j^{\frac{1}{2}} \cdot t_{OX}^{\frac{1}{3}}$$

- The parallel field E_P grows exponentially going to the drain

$$E_P(x) = E_{MIN} \cdot \cosh\left(\frac{x}{\Delta L_E}\right)$$

[1] P.K. Ko *et al.*, in *IEDM Tech. Dig.*, p.600, 1980.

CHE current calculation

- CHE current has been modeled following the approach proposed in [2]
- CHE current electrons must have kinetic energy higher than the Si/SiO_2 barrier (a) and velocity direction toward the gate (b) to be able to pass the oxide potential barrier

(a) To model the non-Maxwellian high energy tail of electron energy distribution we adopted the analytical model used in [3], where χ is determined from Monte-Carlo simulations, E is the electron energy and K is a fitting constant

$$f_{e1}(E,E_P) = K \cdot \exp\left(-\chi E^3 \big/ |E_P|^{1.5}\right)$$

[2] B. Eitan *et al.*, *IEEE Trans. Electron Dev.*, Vol. ED-28(3), pp.328-340, 1981

[3] C. Fiegna *et al.*, *IEEE Trans. Electron Dev.*, Vol. ED-38(3), pp.603-610, 1991

CHE current calculation /2

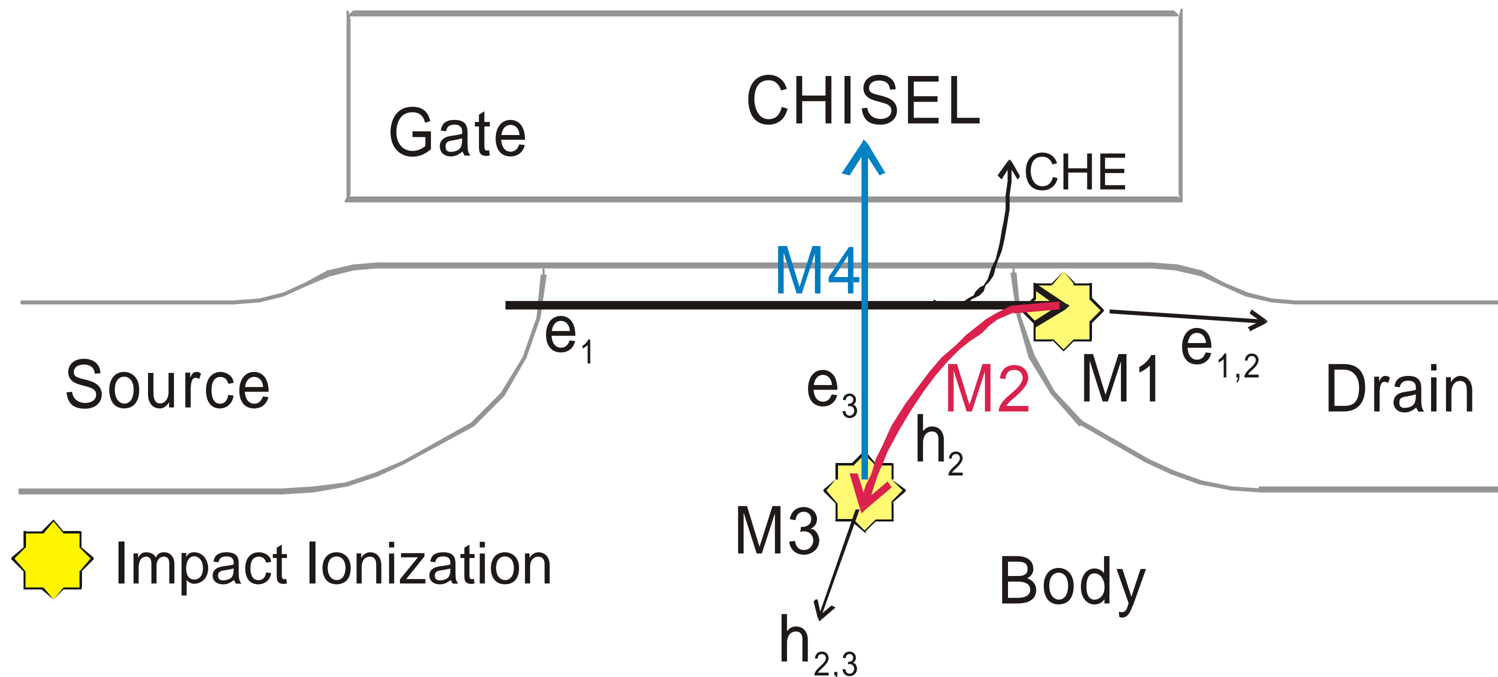
(b) The momentum distribution is considered spherical, being the momentum relaxation time constant much smaller than the energy relaxation time constant

- The probability of an electron to cross the oxide barrier is given by the product of
  - the tunneling probability P_{TUN} calculated by the WKB method
  - the probability that the electron velocity is directed toward the gate P_V
  - the probability that electrons do not loose energy when traveling the distance to the interface P_C

$$I_{CHE} = I_{DS} \int_0^{L_E} \int_0^{\infty} f_{e1}[E,x] \cdot P_{TUN}[E,x] \cdot P_V P_C \cdot dE \cdot dx$$

CHISEL physics

- The key point of CHISEL current modeling is the accurate calculation of energy distribution of carriers involved
- CHISEL electrons are generated by four physical mechanisms (M)



CHISEL physics /2

- CHISEL physical mechanisms: M1) hot electrons e1 ionize producing electron-hole pairs (e2-h2) with multiplication factor M_1; M2) h2 are heated by the high field, M3) and ionize with multiplication factor M_2; M4) electrons e3 are driven toward the Si/SiO_2 interface (M4) gaining some energy from the field.
- The core of this model is given by the new approach to calculate analytically the e3 energy distribution (ED)
- This new approach is based on two functions, called Transformation Functions (TF), that model changes induced by each one of the four physical mechanisms (M1-M4) in the carrier energy distributions

Transformation functions (TF)

- The first TF calculates the ED of carriers generated by impact ionization (secondary) as a function of the ED of generating (primary) carriers. Its main characteristics are:
  - TF mean is at $(E\text{-}E_G)/3$, since a carrier with energy E loses a part of its energy E_G during ionization, and the remaining energy $(E\text{-}E_G)$ is redistributed among the ionizating carrier and the new e/h pair [4]
  - TF is zero at $E\text{-}E_G$ and 0, since the probability for a carrier to have $E\text{-}E_G$ and 0 energy is negligible
  - TF integral is equal to unity.
- With all these constraints, we chose for the first TF a beta distribution function with parameters (a=3 ; b=6)

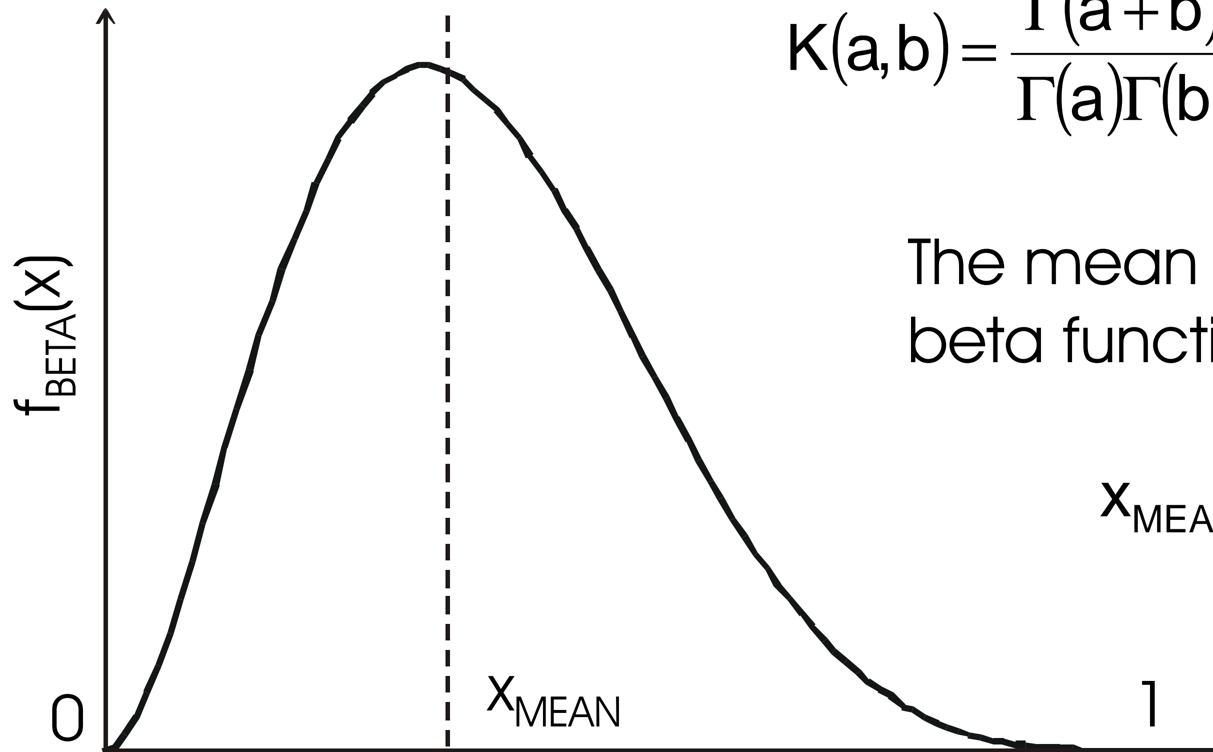
[4] J.D. Bude *et al.*, *IEEE Trans. Electron Dev.*, Vol. ED-47(10), p.1873-1881, 2000.

Beta Function

- For 0<x<1, the beta function is defined as

$$f_{BETA}(x;a,b) = K(a,b) \cdot x^{a-1} \cdot (1-x)^{b-1}$$

$$K(a,b) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}$$



The mean of the beta function is at

$$x_{MEAN} = \frac{a}{a+b}$$

Transformation functions (TF) /2

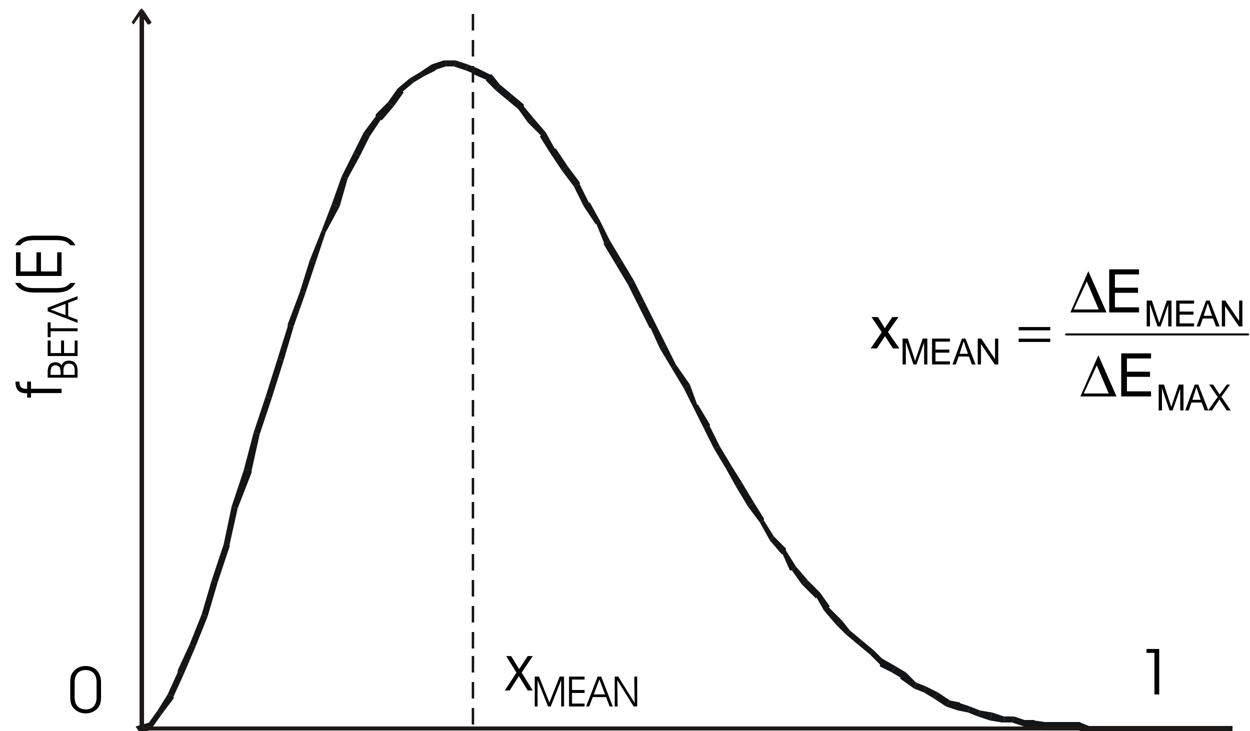
- The second TF models the energy distribution of carriers that have gained energy from the electric field
- ΔE_{MAX} is the maximum energy a carrier can gain if does not suffer any collision (from the potential profile)
- The main TF's characteristics are:
  - it is zero at ΔE_{MAX} and $\Delta E_{MIN}=0$, since the probability for a carrier to gain the ΔE_{MAX} and 0 energy is zero
  - its mean is at E_{MEAN}, that is calculated through

$$\Delta E_{MEAN}(x) = \frac{3}{5}\int_0^x q \cdot F(\xi) \cdot \exp\left(-\frac{x-\xi}{\lambda_\omega}\right) d\xi$$

where F is the electric field and λ_ω is the energy relaxation length along the path followed by carriers

Transformation functions (TF) /3

- TF integral is equal to unity.
- With all these constraints, we chose also for the second TF a beta distribution function



CHISEL current calculation

- The e3 ED $f_{e3}(E)$ is calculated from $f_{e1}(E)$ by applying in series the four transformation function corresponding to the four mechanisms described above
- The h2 ED is calculated from the e1 one through

$$f_{h2}(E) = \int_{E+E_G}^{\infty} M_1 \cdot f_{e1}[E' + E_G, E_P] \cdot f_{beta}\left(\frac{E}{E' + E_G}; a = 3, b = 6\right) \cdot dE'$$

that is: the amount of holes h2 with energy E generated by impact ionization is given by the sum of all primary electrons with energy $E' > E + E_G$ (f_{e1}), multiplied by the probability that they ionize transferring the energy $E' - E$ to the newly generated h2 holes (f_{beta})

CHISEL current calculation /2

- The ED of energetic h2 holes (those that gained energy from the field at the drain junction) is evaluated through

$$f_{h2,E}(E) = \int_{E-\Delta E_{MAX}}^{E} f_{h2}(E') \cdot f_{beta}\left(\frac{E-E'}{\Delta E_{MAX}}; a=3, b=3\left(\frac{\Delta E_{MAX}}{\Delta E_{MEAN}}-1\right)\right) \cdot dE'$$

that is: the amount of energetic holes with energy E is the sum of all the cold holes (those just generated by impact ionization) with energy $E^{I}<E$, multiplied by the probability that they gain the energy $E-E^{I}$

- ΔE_{MEAN} is calculated summing the contribution due to both the lateral and the normal channel field
- The ionization point is calculated equating the distance traveled to the energy relaxation length

CHISEL current calculation /3

- The ED of e3 electrons generated by impact ionization and of
- e3 electrons at the Si/SiO_2 interface have been evaluated following the same procedure adopted to evaluate f_{h2} and $f_{h2,E}$ replacing f_{e1} and f_{h2} with $f_{h2,E}$ and f_{e3} respectively
- Then, CHISEL current is given by

$$I_{CHISEL} = I_{DS} \int_0^{\infty} f_{e3}(E) \cdot P_{TUN}(E) \cdot dE$$

Simulation results

- We simulated CHE-CHISEL current on a 0.25 μm MOS transistor manufactured by STMicroelectronics
- The I gate current, I_G, has been measured through

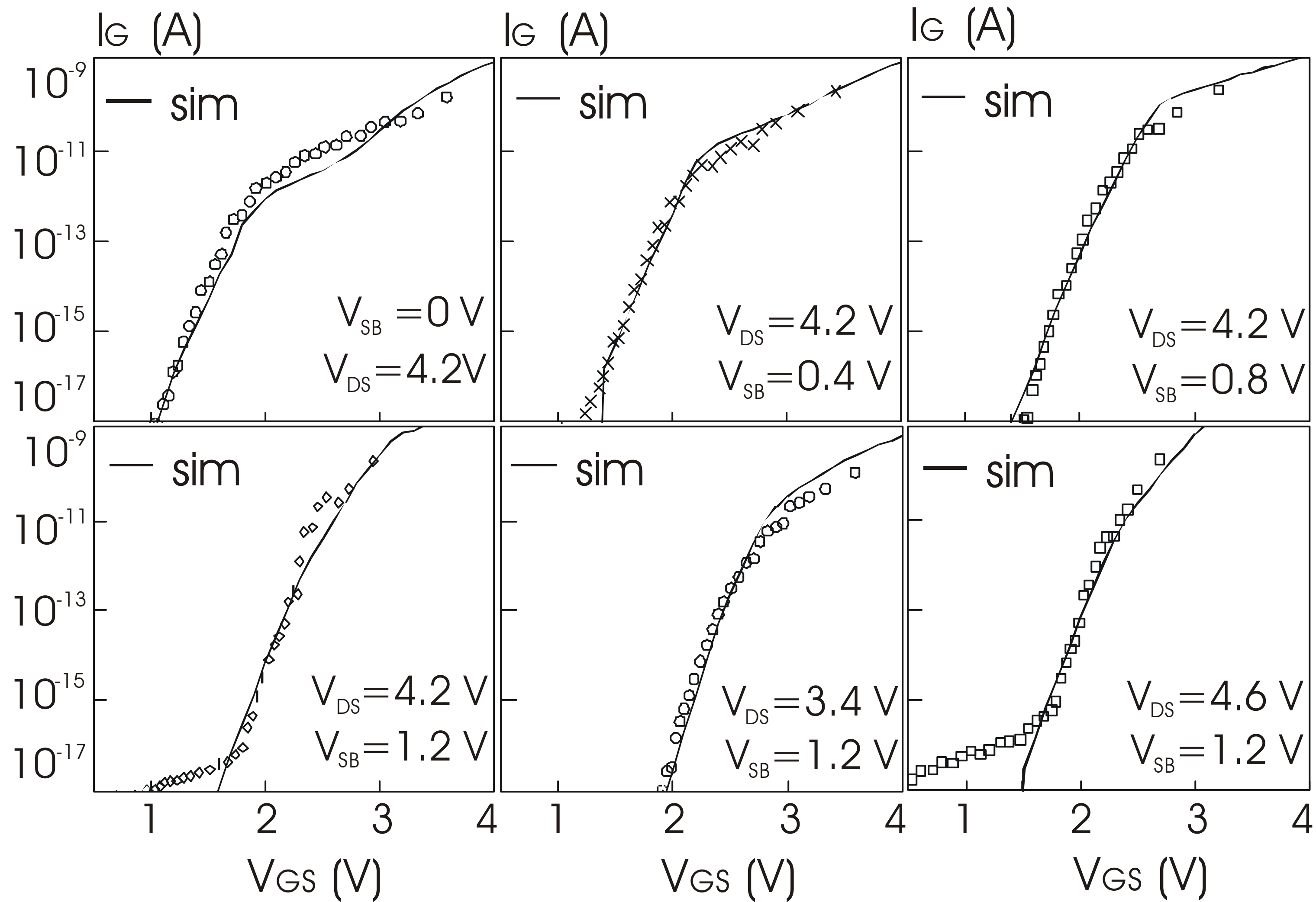
$$I_G = C_{CG} \cdot \frac{dV_T}{dt}$$

V_T is the threshold voltage measured on an equivalent Flash memory and C_{CG} is the capacitance between control and floating gates of the Flash cell

- The FG potential of the Flash memory corresponds to the gate voltage V_{GS} of the simulated MOS transistor, and it has been calculated by means of the model proposed in [5]

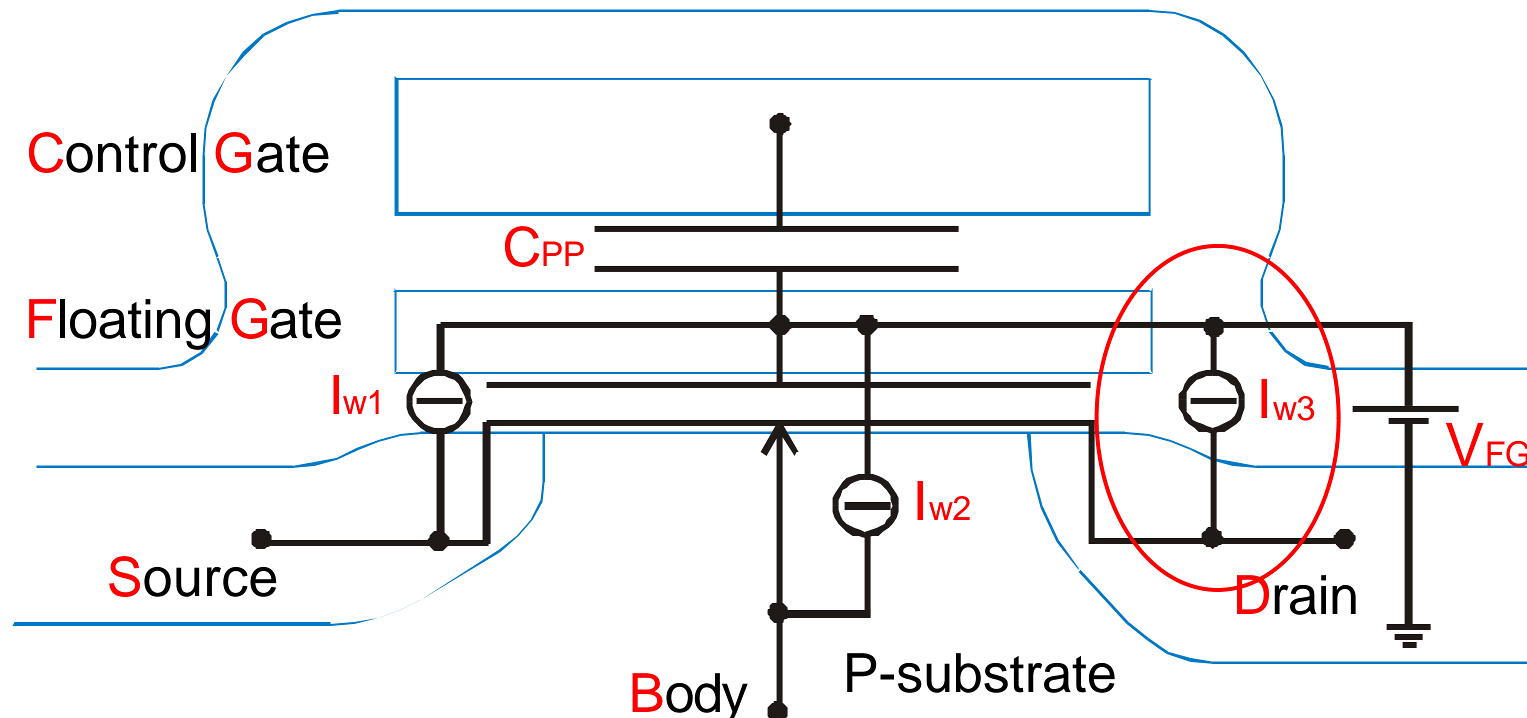
[5] L. Larcher *et al.*, in *Proc.* MSM 2001, pp. 56-59, 200.

Simulated and measured I_G-V_{GS}



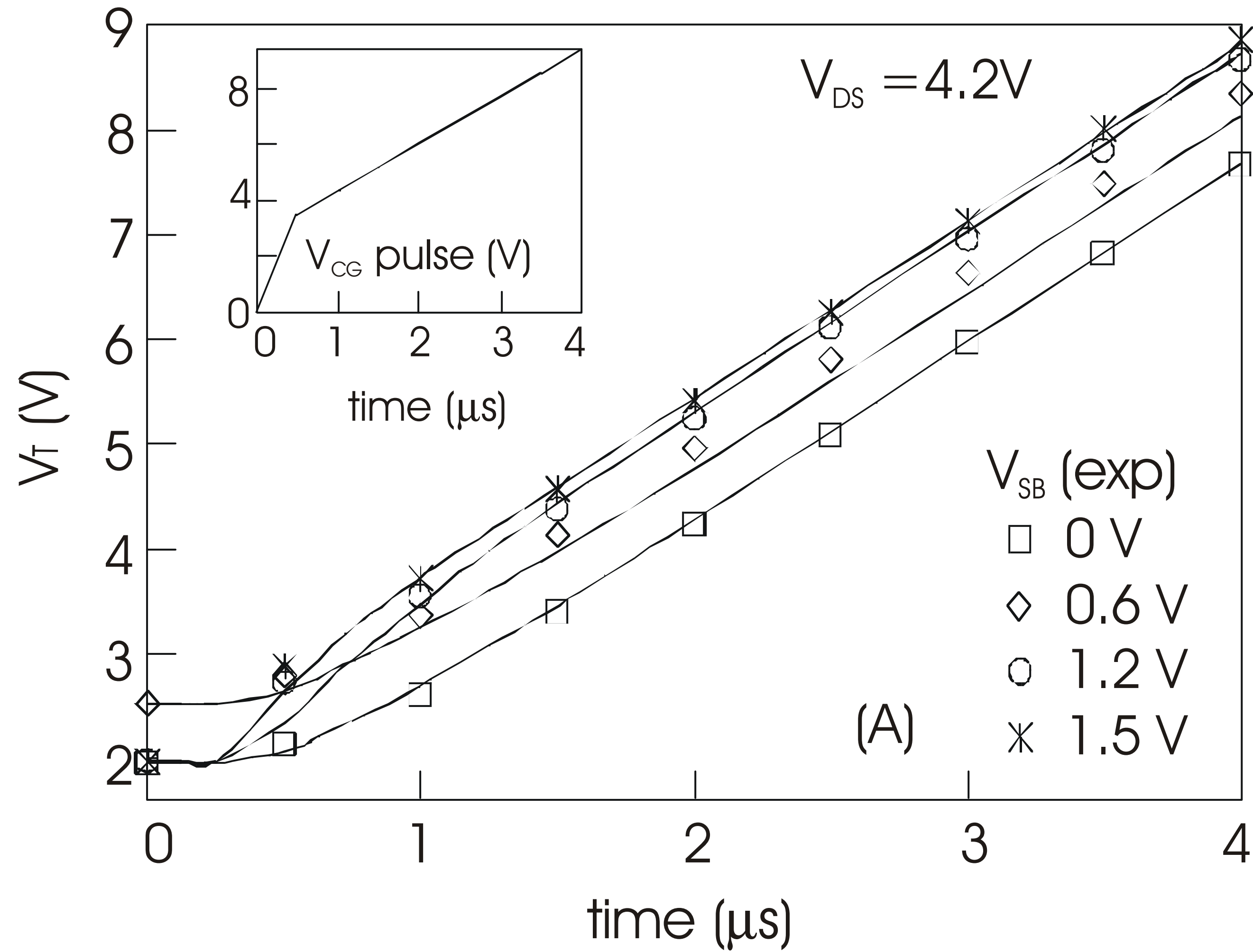
Simulation results /2

- The CHE-CHISEL current model has been included in the Flash memory model proposed in [5] by means of the voltage controlled current source I_{W3}

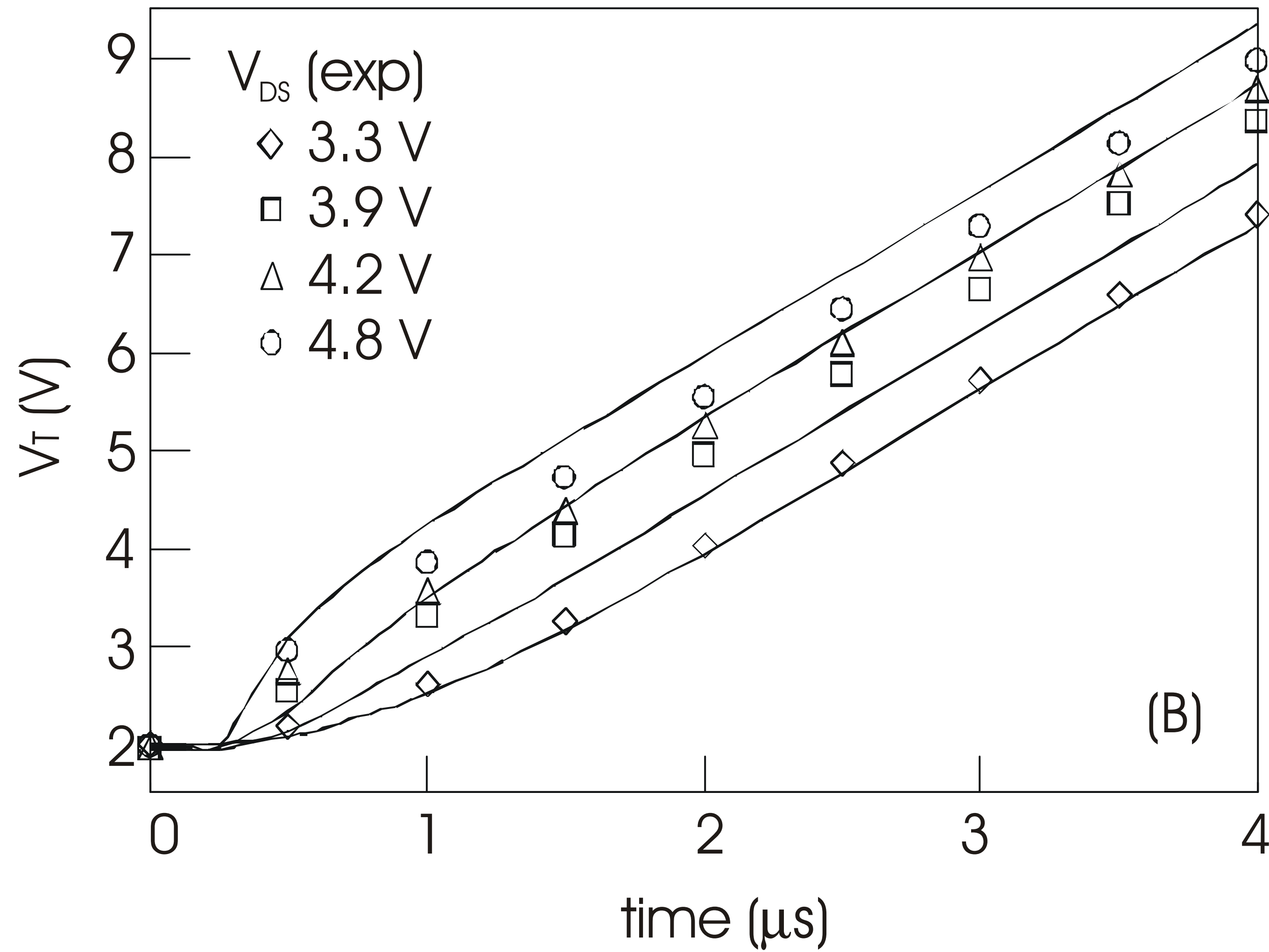


[5] L. Larcher *et al.*, in *Proc.* MSM 2001, pp. 56-59, 200.

Flash Program curves: V_T vs time



Flash Program curves: V_T vs time /2



Conclusions

- For the first time a new analytical model of hot carrier gate current including CHISEL injection mechanisms
- This model is capable to simulate CHE - CHISEL gate currents correctly
- This allows to take into account of CHE-CHISEL effects in simple circuit simulations
- The accuracy of results cannot be compared to MC techniques (many approximations taken), but results obtained fit well experimental data
- Future work will be devoted to validate single parts of the model through the comparison with Monte-Carlo simulations