# Compact modeling of multigate MOSFETs

## *COMON European project.*

*MUGFET modeling in cooperation with:*

- University of Strasbourg (France)

*Prof. Christophe Lallement, Dr. Fabien Pregaldini,*
*Nicolas Chevillon (PhD student )*

- University of Tarragona (Spain)

*Prof. Benjamin Iniguez*

# Compact modeling of multigate MOSFETs

Why using more than one gate in field effect transistors ?

- Better control of ‘electrostatics’ in the channel.

- Less ‘2D’ induced drain effects, i.e. less short channel effects.

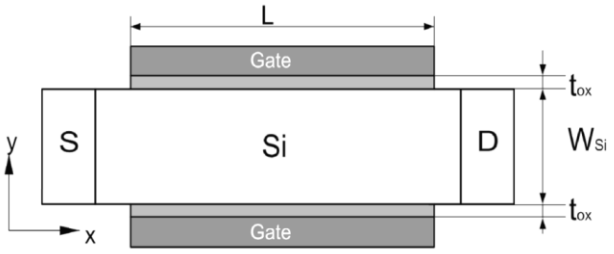
- If undoped silicon, improved mobility with ‘no’ random dopant fluctuations.

- No substrate voltage dependent depletion , i.e. ideal subthrehold slope (60 mV/dec)

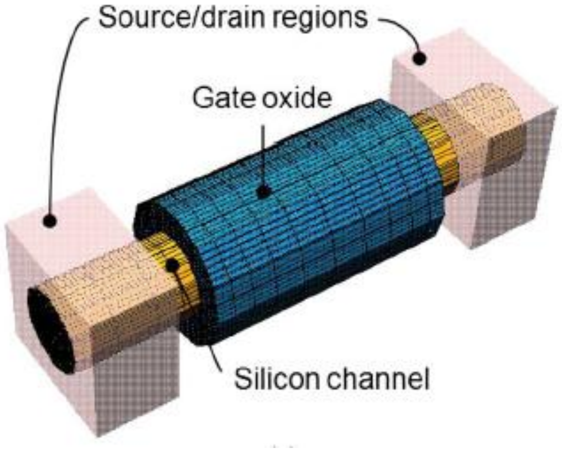
# Compact modeling of multigate MOSFETs

## Different architectures:

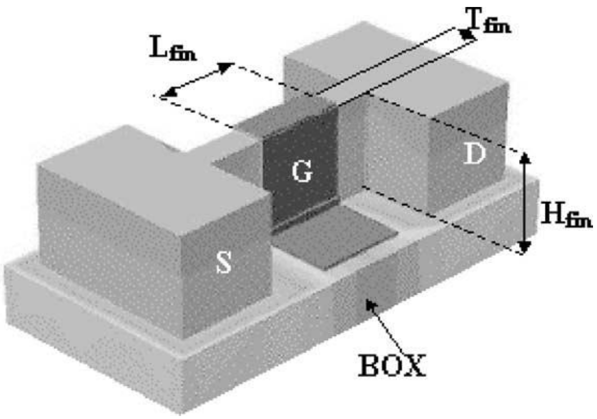
- The double gate MOSFET
  Independent gates offer two options:
  - *Symmetric operation*
  - *Asymetric operation*



- The Gate All Around (nano wire) MOSFET



- The FinFET



# Compact modeling of multigate MOSFETs

Two principles of operation for MUGFETs:

- Inversion mode operation:
  - Almost undoped silicon
  - Junctions are created for source and drain
  - The current flows mainly at $Si/SiO_2$ interfaces

- Depletion-Accumulation operation:
  - Highly doped silicon
  - No source and drain junctions (junction less devices)
  - The current flows in the volume, and not at the interfaces.

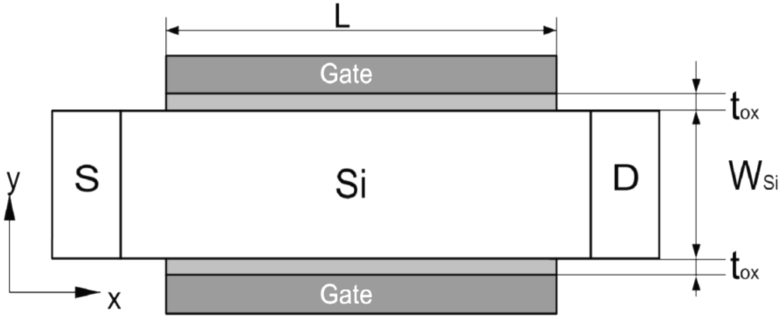
# Compact modeling of multigate MOSFETs: the undoped DG MOSFET

The symmetric junction based DG MOSFET model.

- Charge based model (not $V_T$ based)
- Charge conservation ensured
- Q-V and I-V analytical relations
- Explicit Q-V dependences
- Short channel effects and QM corrections included
- Complete CV quasi – static model

# Compact modeling of multigate MOSFETs: the undoped DG MOSFET

## **Core** of the generic charge based model:



Normalization: charge: $q = \dfrac{Q}{4C_{ox}U_T}$

voltage: $v = \dfrac{V}{U_T}$ , current: $i = \dfrac{I_D}{I_{SP}}$

with $U_T$ the thermodynamic voltage

and $I_{SP}$ the specific current

Normalized charge-potentials relationship:

$$v_g - v_{to} - v_{ch} = 4 \cdot q_g + \ln(q_g) + \ln\ (1 + \alpha \cdot q_g) \text{ with } \alpha = \frac{C_{ox}}{\varepsilon_{Si}/W_{Si}}$$

$$\Rightarrow \quad q_g = f(v_g - v_{to} - v_{ch})$$

Normalized drain current:

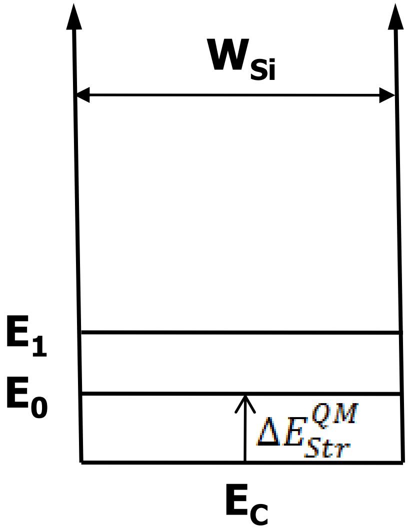
$$i = -{q_m}^2 + 2 \cdot q_m + \frac{2}{\alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right)\Big|_{q_{mS}}^{q_{mD}} \text{ with } q_m = -2 \cdot q_g$$

# Compact modeling of multigate MOSFETs: quantum confinement effects

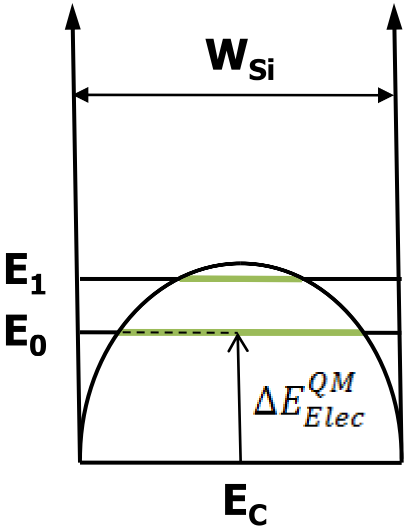
## Principle of the quantum mechanical corrections

Quantum shift of the fundamental energy level: 2 contributions

$$\Delta E_0^{QM} = \Delta E_{Str}^{QM} + \Delta E_{Elec}^{QM}$$



*Structural confinement*



*Electrical confinement*

# Compact modeling of multigate MOSFETs: quantum confinement effects

These quantum corrections are included analytically:

New charge-potentials relationship:

$$v_{gN}^{QM} - v_{to} - v_{ch} = 4 \cdot q_g + \ln q_g + \ln\left(1 + \alpha \cdot q_g\right) + \boxed{\mathrm{A}^{\mathrm{QM}} \cdot q_m^{2/3}}$$

Normalized drain current expression:

$$i = -{q_m}^2 + 2 \cdot q_m + \frac{2}{\alpha} \cdot \ln\left(1 - \frac{\alpha}{2} \cdot q_m\right) + \boxed{\frac{2}{5} \cdot \mathrm{A}^{\mathrm{QM}} \cdot q_m^{5/3}} \Bigg|_{q_{mS}}^{q_{mD}}$$

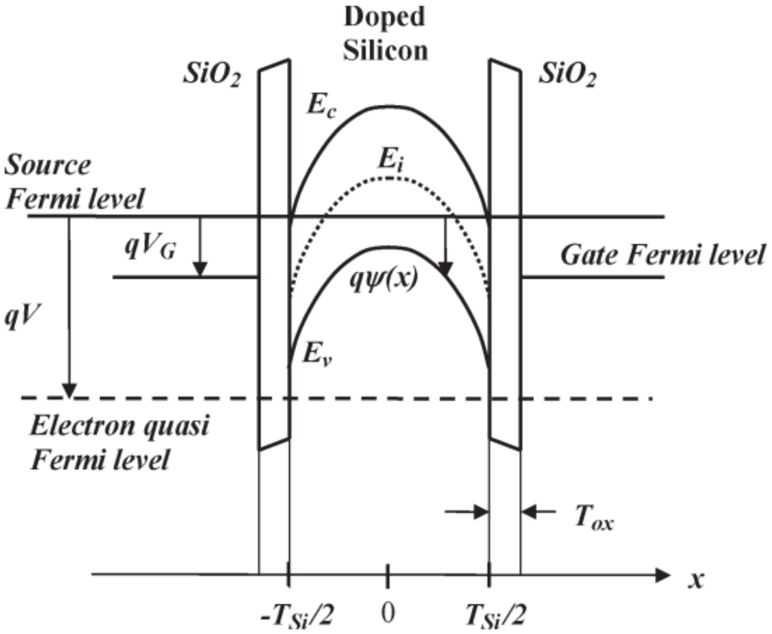
*No empirical parameter is needed*

*‘only ’ and  additionnal term in the drain current expression*

# Compact modeling of multigate MOSFETs: Doped DG MOSFETs

## The doped DG MOSFET and the equivalent-thickness concept

Energy diagram of an P type doped Si channel



Including the doping $N_a$ in the Poisson's equation,

$$\frac{d^2\psi}{dx^2} = \frac{q}{\varepsilon_{Si}} \cdot \left( n_i \cdot e^{\frac{\psi - V}{U_T}} + N_a \right)$$

… but then, no analytical solution can be found …

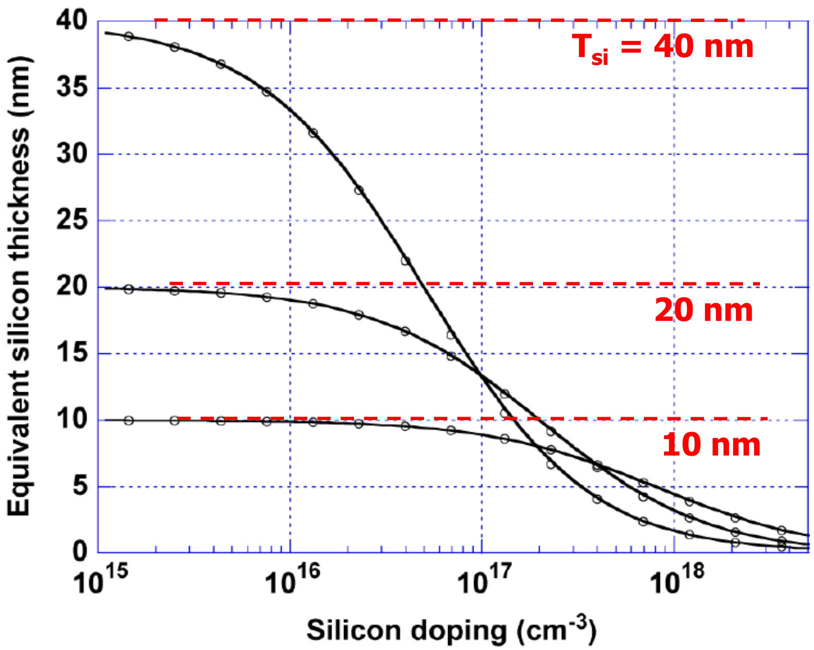
# Compact modeling of multigate MOSFETs: Doped DG MOSFETs

…but if we define an equivalent thickness, which is doping dependent, we can still used the undoped core model

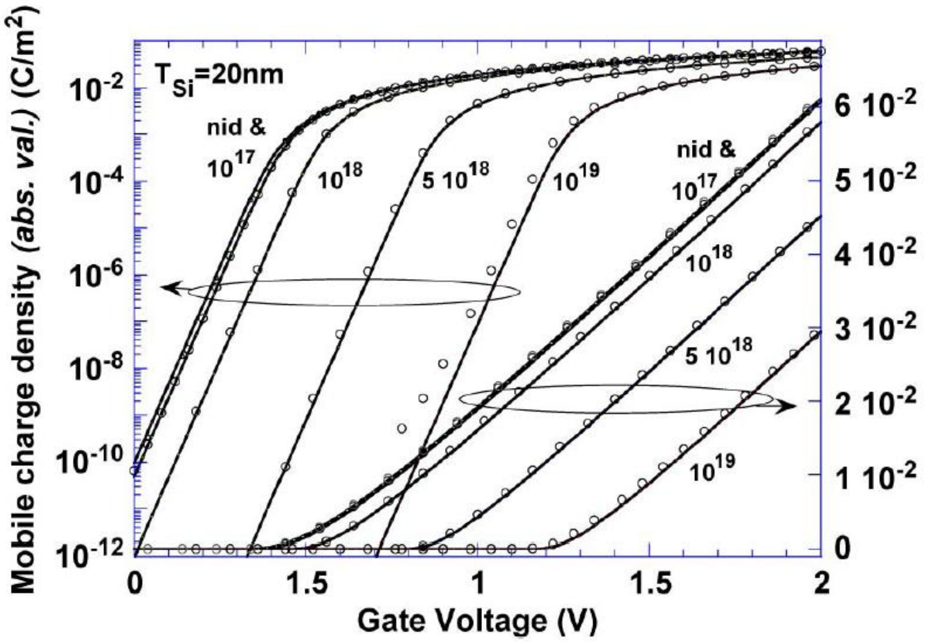
$$\frac{1}{\frac{T_{\mathrm{eq}}}{2}} = \frac{1}{\int\limits_{-T_{\mathrm{Si}}/2}^{0} e^{\frac{X}{T_{\mathrm{Si}}\cdot\varepsilon_{\mathrm{Si}}\cdot U_T}\cdot x^2}\,dx} + \frac{X}{\varepsilon_{\mathrm{Si}}\cdot U_T}$$

$$\mathit{with} \quad X = \frac{q\cdot N_a\cdot T_{Si}}{2}$$

*Equivalent thickness*

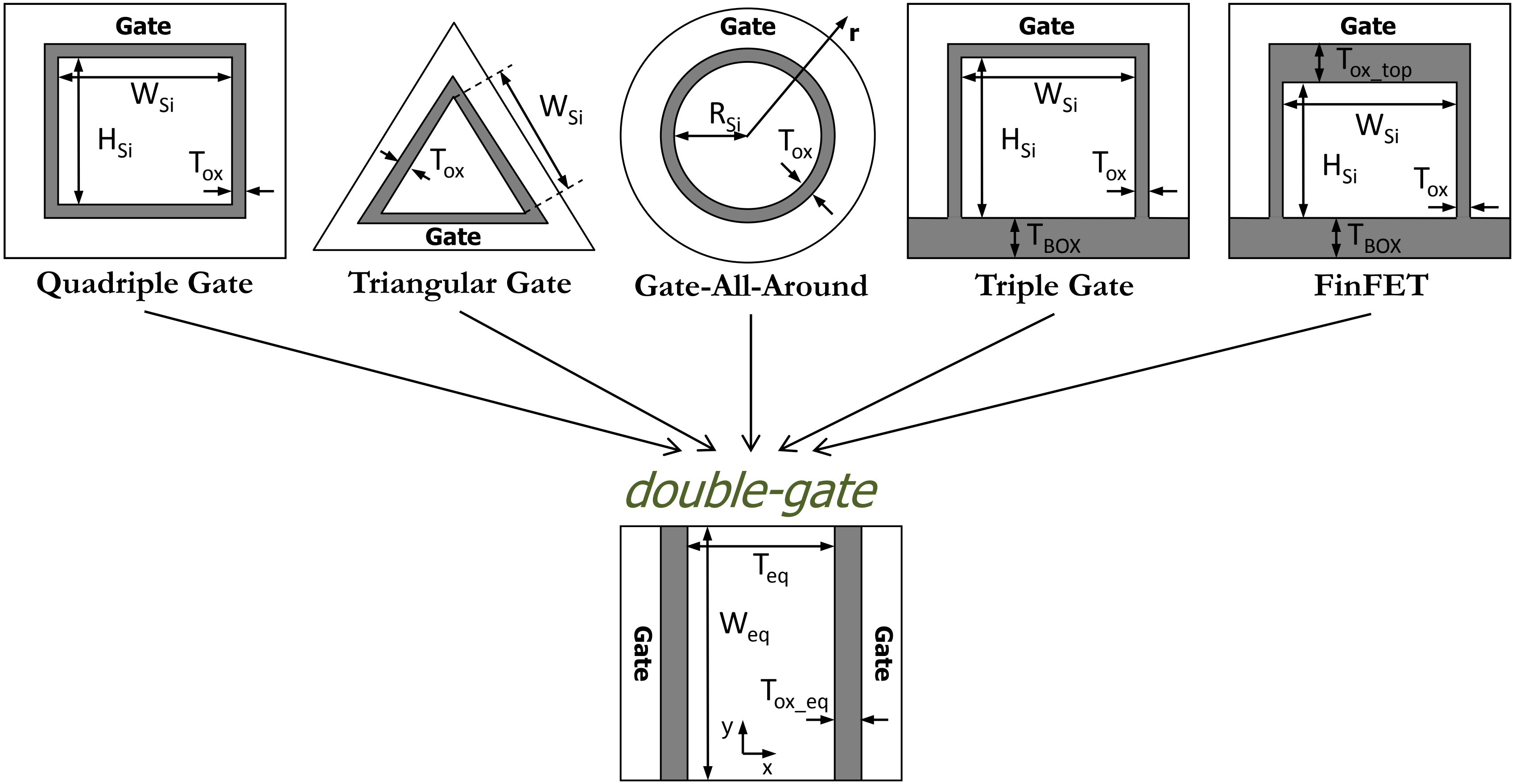


*Mobile charge density*



# Compact modeling of multigate MOSFETs: Arbitrary undoped multigate MOSFET geometries

## *Principle of multigate MOSFETs 'planarization'*



**Quadriple Gate** **Triangular Gate** **Gate-All-Around** **Triple Gate** **FinFET**

*double-gate*

Key parameters: $T_{eq}$, $W_{eq}$ and $C_{ox\_eq}$

# Compact modeling of multigate MOSFETs: Arbitrary undoped multigate MOSFET geometries

## Generalization of geometrical parameters:

Equivalent thickness: $T_{eq} = \dfrac{2 \cdot S}{P}$ S, the silicon cross section area

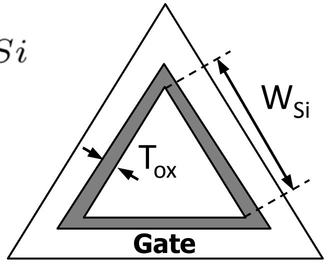
Equivalent width: $W_{eq} = \dfrac{P}{2}$ P, the gate perimeter

and the equivalent silicon capacitance $C_{Si\_eq} = \dfrac{\varepsilon_{Si}}{T_{eq}}$

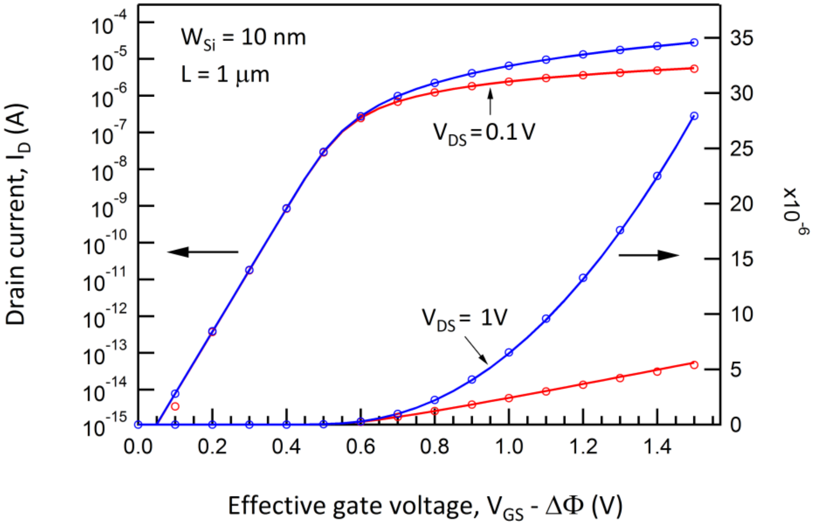
## *Validity of the generalization for a Triangular Gate MOSFET:*

$$T_{eq} = \frac{1}{3}\sqrt{{W_{Si}}^2 - \left(\frac{W_{Si}}{2}\right)^2}$$

$$W_{eq} = \frac{3}{2} W_{Si}$$



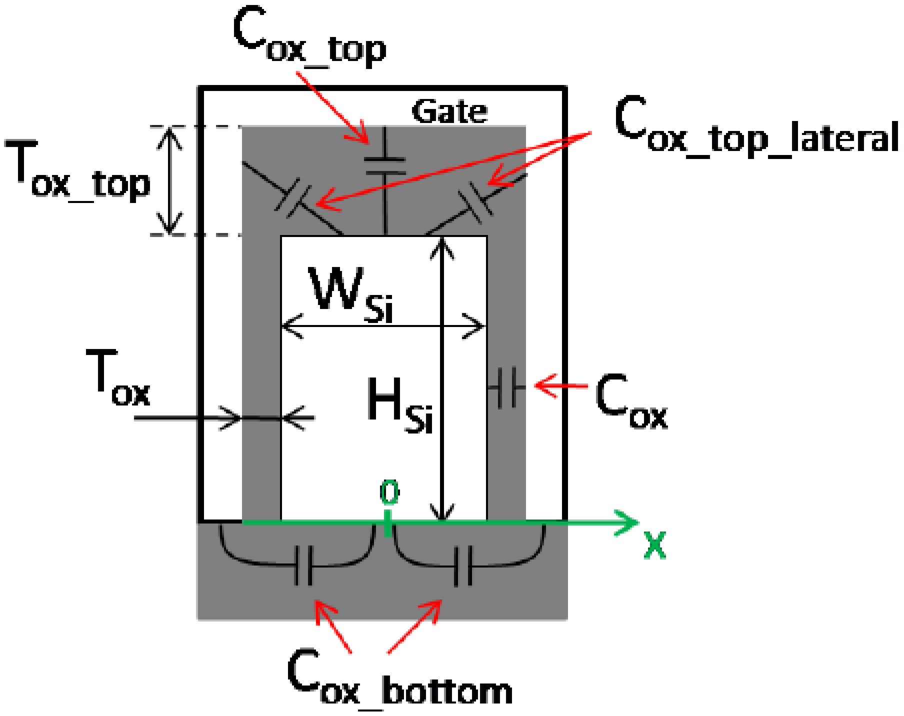
Triangular Gate



# Compact modeling of multigate MOSFETs: Arbitrary undoped multigate MOSFET geometries

## Generalization of geometrical parameters: equivalent gate capacitance

$$C_{ox\_eq}=\frac{C_{ox}\cdot H_{Si}+C_{ox\_top\_eq}\cdot W_{Si}/2+C_{ox\_bottom}\cdot W_{Si}/2}{H_{Si}+W_{Si}}$$

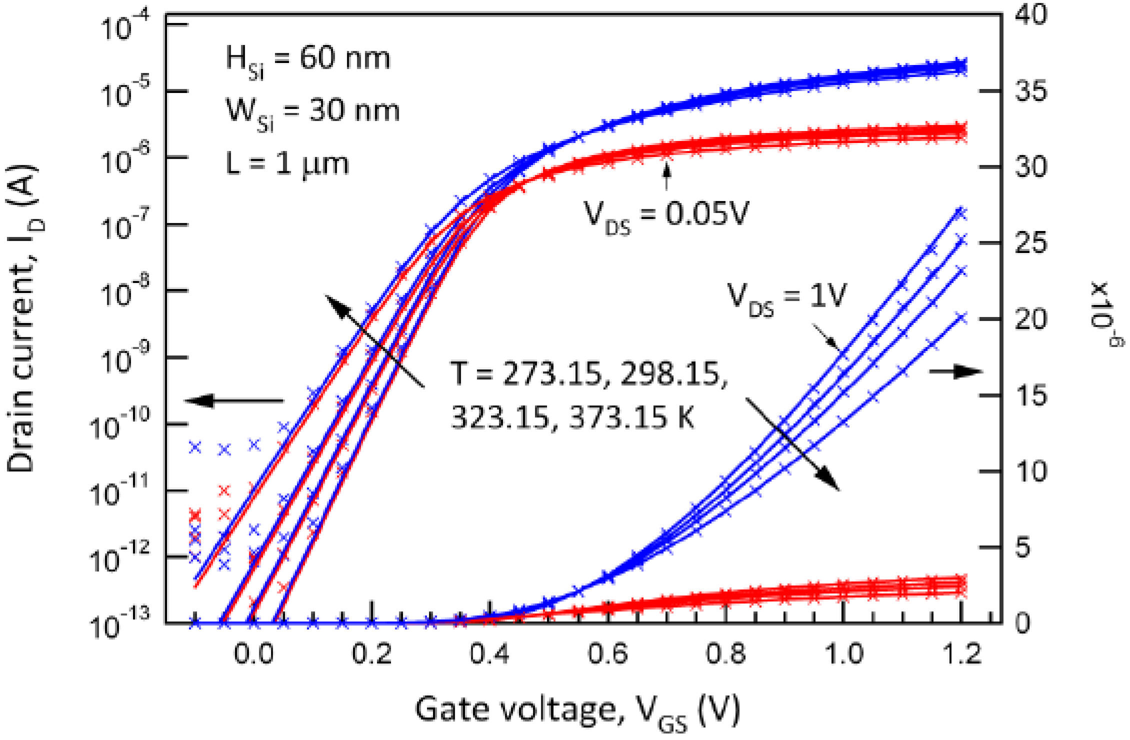


## Generalization:

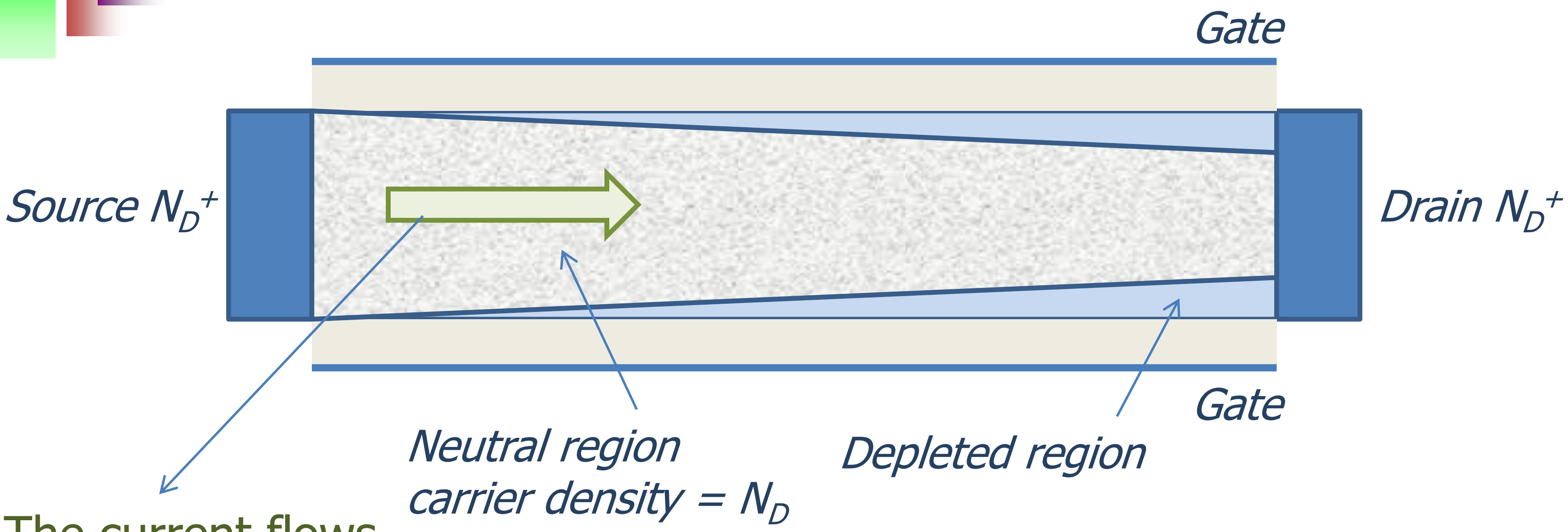
$$C_{ox\_eq}=\frac{\sum_{i=1}^{n}C_i\cdot L_i/2}{\sum_{i=1}^{n}L_i/2}=\frac{\sum_{i=1}^{n}C_i\cdot L_i}{\sum_{i=1}^{n}L_i}$$

# Compact modeling of multigate MOSFETs: Arbitrary undoped multigate MOSFET geometries

## Generalization of geometrical parameters: Model vs Measurement on a long channel TG FET (Intel data)



# Compact modeling of multigate MOSFETs: The junction less DG MOSFET



The current flows inside silicon

*Looks like a JFET in which junctions have been replaced by oxide layers and gate electrodes*

# Compact modeling of multigate MOSFETs: The junction less DG MOSFET

The ‘junction’ DG MOSFET solution is no longer valid .

A new approach/model is needed.

If the device operates in depletion, we obtain:

$$V_G - V - \Delta\phi - U_T \cdot \ln\left(\frac{N_D}{n_i}\right) \overset{dep}{\approx} -\frac{{Q_{SC}}^2}{8 \cdot q \cdot N_D \cdot \varepsilon_S} - \frac{Q_{SC}}{2 \cdot C_{ox}} + U_T \cdot \ln\left(1 - \left(\frac{Q_{SC}}{q \cdot N_D \cdot T_{sc}}\right)^2\right)$$

If the device operates in accumulation, we obtain:

$$V_G - V - \Delta\phi - U_T \cdot \ln\left(\frac{N_D}{n_i}\right) \overset{acc}{\approx} \frac{-Q_{SC}}{2 \cdot C_{ox}} + U_T \cdot \ln\left(1 + \frac{{Q_{SC}}^2}{8 \cdot q \cdot N_D \cdot \varepsilon_{Si} \cdot U_T}\right)$$

The current can then be calculated for both regimes

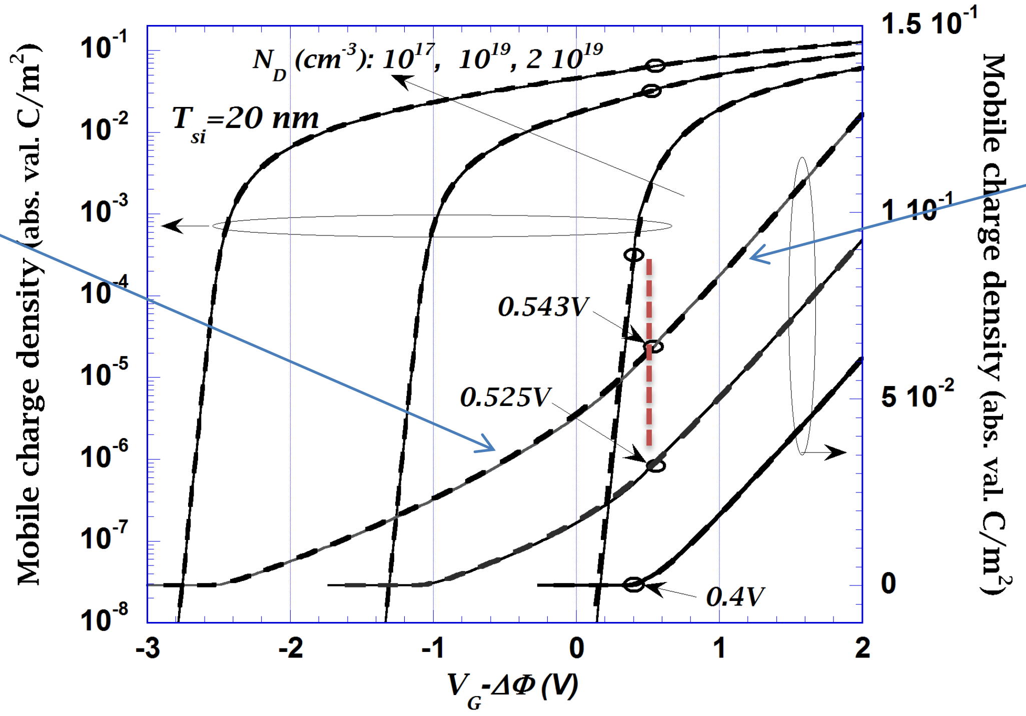
… but it may also happen that *part of the channel is in ‘depletion’, and part is in ‘accumulation’* : **the hybrid channel case.**

# Compact modeling of multigate MOSFETs: The junction less DG MOSFET

*Depletion*

*In this region, the mobile charge ~ $V_G^{0.5}$*

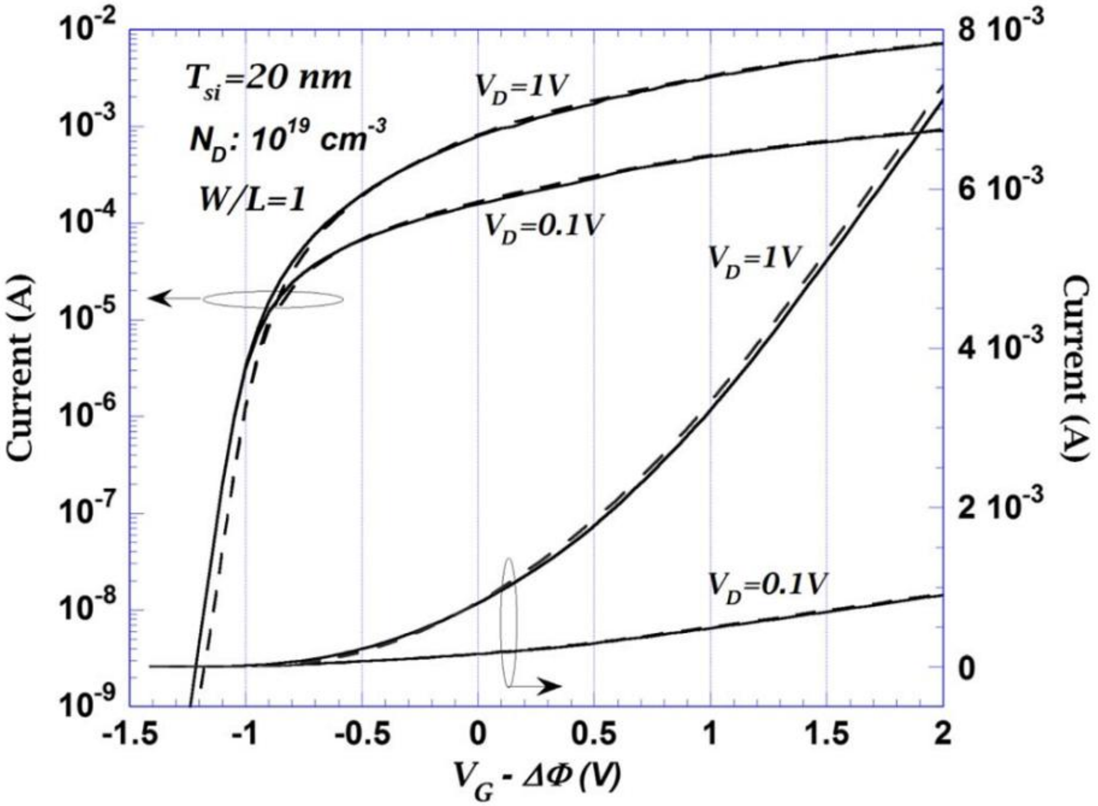
*Cannot be predicted by 'junction based' DG models .*



*Accumulation*

*… looks like 'junction based' DG models .*

# Compact modeling of multigate MOSFETs: The junction less DG MOSFET



Current -voltage characteristics of highly doped DG JL FET versus TCAD simulations.

Continuity is ensured in all regions of operation.

# Compact modeling of multigate MOSFETs: The VESFET

## Current research on ‘VESFET’ technology.

Fabrication and Modeling asymmetric operation in junction less devices with independent gates.