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HSP: A Surface-Potential-Based Compact Model of AlGaN/GaN HEMTs Power Transistors

Patrick Martin and Rereao Hahe

patrick.martin@cea.fr

CEA, Leti, Silicon Components Division,

Simulation and Modeling Laboratory,

Minatec Campus, Grenoble, France.

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Summary

- Motivation
- Existing models for GaN power transistors, need for a more physical model
- GaN material specificity for power transistors
- HSP model flow
- AlGaN/GaN energy band diagram and electrostatics
- Analytical E_F calculation, a tedious mathematical!
- Comparison of Numerical & Analytical E_F calculation
- Velocity saturation and mobility model
- Self-heating modeling
- Doping of AlGaN by ion implantation
- Calculation of drain current
- Intrinsic charge model
- HSP model parameter list
- Results: parameter extraction, DC, self-heating
- Summary and conclusions

Motivation

- Low cost, high performance devices used in energy conversion electronic circuits
- Applications: mainly switching applications, not analogue/RF amplification
- Low cost if substrate diameter greater than 4“ - 100 mm (SiC)
- High performance: high switching speed
- GaN is a promising candidate for power applications (1200 V - 300 A, power ~ kW, high operating temperature about 250 °C)
- High breakdown field > 3 MV/cm
- High mobility in HEMT (High Electron Mobility Transistor)
- High electron saturation velocity: 1.2 10^7 cm/s
- Wide bandgap semiconductor
- AlGaN/GaN HEMTs

Existing models for GaN power transistors

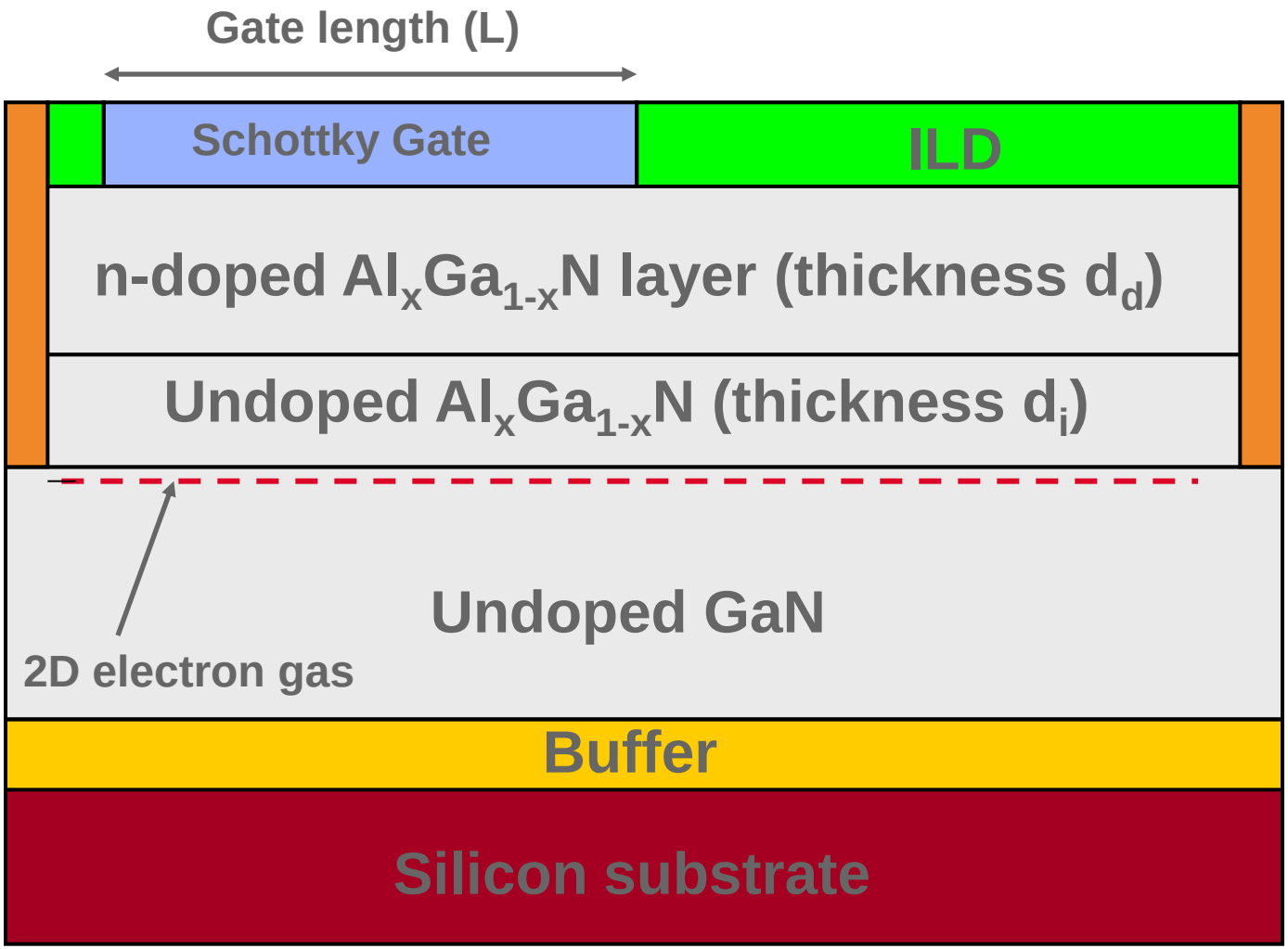
- Macro-models using SPICE G source (or VCCS): one device, one set of parameters (e.g. EPC*)
- Empirical models such as cubic Curtice and Angelov (or Chalmers) models
- Threshold-voltage based, piece-wised model (weak, strong, moderate “inversion”)
- Surface-potential-based (since 2010-2011, John’10, Cheng’11, Khandelwal’12), iterative or analytical solving for Φ_s
- The last approach is relatively new and driven by analog/RF applications (need for accurate modeling of distortion in medium power amplifiers)

*EPC: www.epc-co.com/

Need for a more physical model

- A HEMT transistor is not a MESFET or a MOSFET (III-V compounds, inversion charge, mobility, …)
- Many materials properties are Al-content and temperature dependent (Eg, σ, …)
- Heterostructures growth technique has a strong impact on electrical properties
- HP devices will work at high temperature
- Self-heating effects will be very important
- Refractory compounds: donors are not fully ionized at RT, the ratio Nd^+/Nd is temperature-dependent

AlGaN/GaN HEMT schematic structure



Lattice constants:

a_{Si}=0.54 nm
a_{GaN}=0.32/0.51 nm (a/c axis)
Important Δa/a

Thermal conductivity:

K_{Si}=150 W/m.K
K_{GaN}=130
K_{SiC}=320

GaN material specificity for power transistors

- Large conduction band discontinuity ΔE_c between AlGaN and GaN: 2-Dimensional Electron Gas (2DEG)
- ΔE_c alone is not sufficient to explain very high charge sheet density of the 2DEG, in excess of 10^{13} cm^{-2}, even without intentional doping
- Additional effect: polarization-induced sheet carrier concentration leading to a strong confinement of 2DEG
  - 1 - Spontaneous polarization (SP) due to anion/cation in lattice, resulting electrical field=3 MV/cm
  - 2 - Piezoelectric polarization (PZ) proportional to strain: $\Delta a(x) = a(Al_xGa_{1-x}N) - a(GaN)$, electrical field=2 MV/cm
- Drawback: Normally-on transistors (depletion mode)
- Work in progress for normally-off HEMTS for safety reasons
- Only N-HEMTs

Contributions to the offset voltage

$$V_{off} = \Phi_B - \Delta E_c - \frac{q N_d d_d^2}{2\varepsilon_{Al_xGa_{1-x}N}} - \frac{q\sigma}{\varepsilon_{Al_xGa_{1-x}N}}\left(d_d + d_i\right)$$

Total polarization σ (spontaneous + piezoelectric) is the main contribution to the offset voltage V_{off}

MOCVD: Ga face, MBE: N-face
Typical x_{Al}: 0.15-0.5
Donors: Silicon Nd=2 10^{18} cm^{-3}

σ positive σ negative

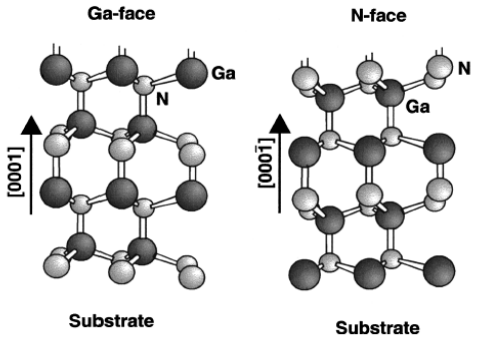
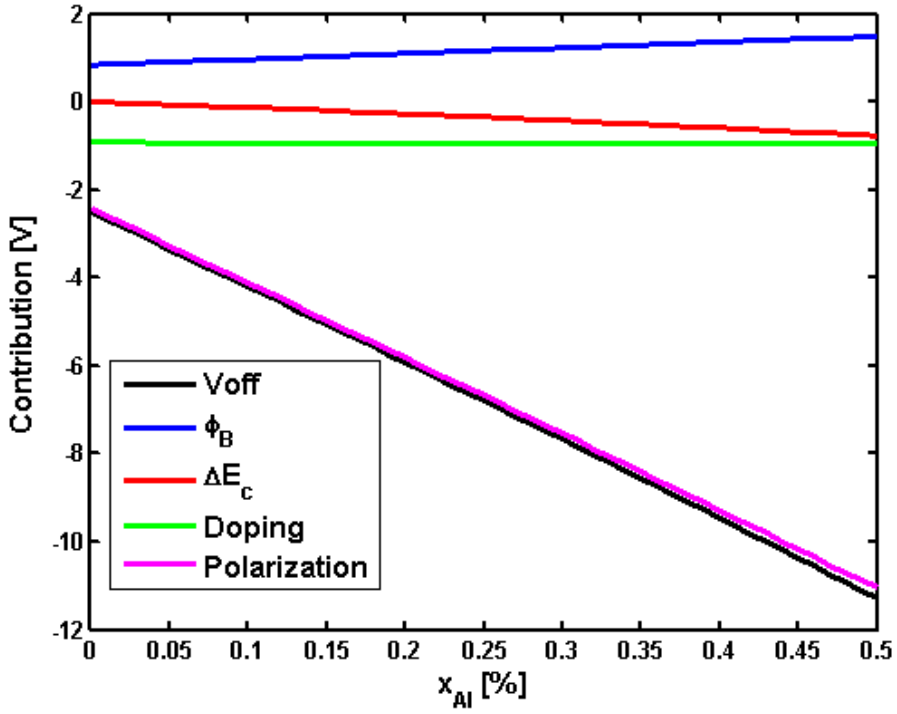
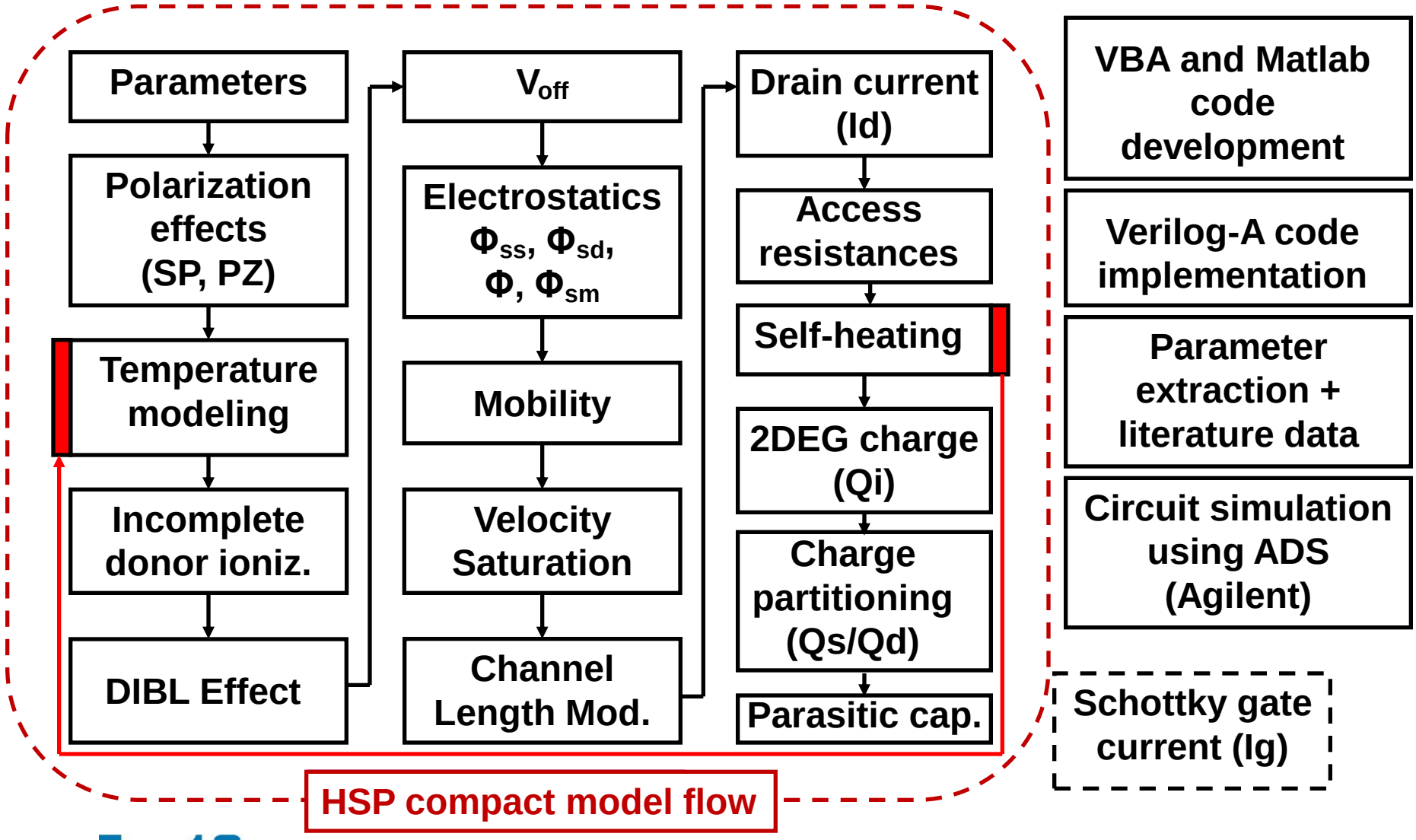


FIG. 4. Schematic drawing of the crystal structure of wurtzite Ga-face and N-face GaN.

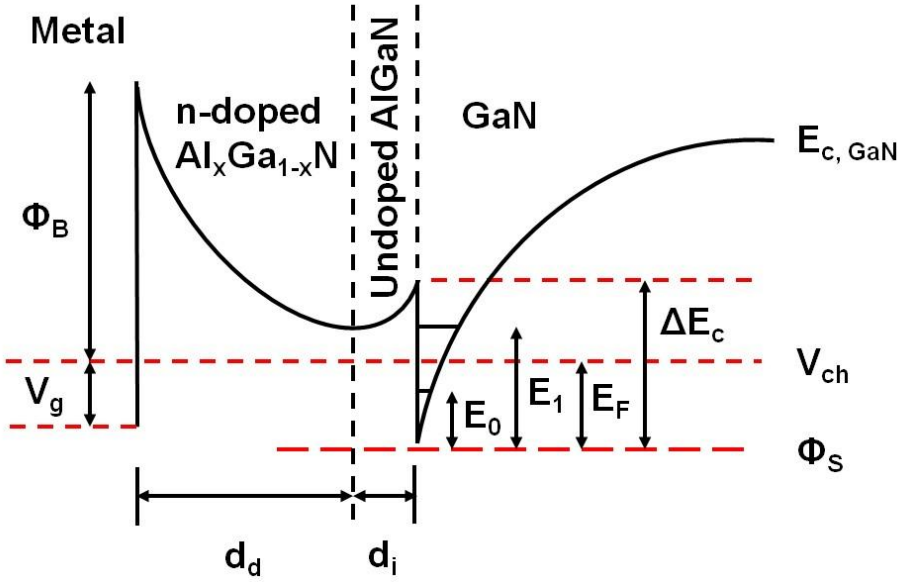


From Ambacher'99
Wurtzite= hexagonal form

A Surface-Potential-Based Compact Model of AlGaN/GaN HEMTs Power Transistors: HSP model flow



AlGaN/GaN energy band diagram and electrostatics



Numerical resolution for E_F ⟶

Assumptions:

- **Triangular potential well**
- **Only the first quantum state, E_0, is considered, E_1 is neglected**

Self-consistent solving of Schrödinger's and Poisson's equations

2DEG sheet carrier concentration n_s:

$$\begin{cases} n_s = \dfrac{\varepsilon_{AlGaN}}{q\,d}\left(V_g - V_{off} - E_F\right) \\ n_s = D\,kT\,Ln\left[1+\exp\left(\dfrac{E_F - E_0}{kT/q}\right)\right] \end{cases}$$

$$V_{off} = \Phi_B - \Delta E_c - \frac{q\,N_d\,d_d^2}{2\,\varepsilon_{AlGaN}} - \frac{q\,\sigma}{\varepsilon_{AlGaN}}\left(d_d + d_i\right)$$

$$E_0 = C_0\,n_s^{2/3}$$

$$D = 4\pi\,m^*/h^2$$

Analytical E_F calculation

- **Analytical determination of E_F is done in two steps:**
- **$E_F = \eta + \omega$**
  - **1 - Approximate solution (η) for two asymptotic cases: (a) for high n_s and (b) for low n_s**
  - **2 - Small refinement (ω), important for medium n_s**
- **Refinement is done several times (5-10) to ensure good accuracy for medium n_s**
- **Surface-Potential (Φ_s) calculation: $\Phi_s = E_F + V_{channel}$**
- **At source: $\Phi_{ss} = E_F + V_s$, at drain: $\Phi_{sd} = E_F + V_d$**

A tedious mathematical development around E_F analytical calculation!

Calcul du coefficient de raffinement w :

En écrivant notre solution $E_F = \eta + w$ et en modifiant l'équation (6) :

$$\ln(1+\exp(\frac{(\eta+w)-u_1(C_{ox}(v_{go}-\eta))^{2/3}}{v_q})) = \frac{v_{go}-(\eta+w)}{a_1}$$

Cette équation que l'on fait passer en exponentielle est le point de départ du calcul de w:

$$1+\exp(\frac{(\eta+w)-u_1(C_{ox}(v_{go}-\eta))^{2/3}}{v_q}) = \exp(\frac{v_{go}-(\eta+w)}{a_1})$$

Commençons par la partie droite de l'équation :

$$\exp(\frac{v_{go}-(\eta+w)}{a_1}) = \exp(\frac{v_{go}-\eta}{a_1})\exp(\frac{-w}{a_1})$$

en posant $\exp((v_{go}-\eta)/a_1) = e_2$ et en réécrivant le terme $\exp(-w/a_1)$ en utilisant un développement limité à l'ordre 2 :

$$\exp(\frac{v_{go}-(\eta+w)}{a_1}) = e_2(1-\frac{w}{a_1}+\frac{w^2}{2a_1^2})$$

De la même manière pour le membre de gauche :

$$1+\exp(\frac{(\eta+w)-u_1(C_{ox}(v_{go}-\eta+w))^{2/3}}{v_q})$$

$$=1+\exp(\frac{(\eta+w)}{v_q})\exp(\frac{-u_1(C_{ox}(v_{go}-\eta))^{2/3}(1-w/(v_{go}-\eta))^{2/3}}{v_q})$$

En posant $\eta_1 = u_1(C_{ox}(v_{go}-\eta))^{2/3}$:

$$=1+\exp(\frac{(\eta+w)}{v_q})\exp(\frac{-\eta_1(1-w/(v_{go}-\eta))^{2/3}}{v_q})$$

On fait alors un développement limité à l'ordre 2 du terme $(1-w/(v_{go}-\eta))^{2/3}$ d'où

$$=1+\exp(\frac{(\eta+w)}{v_q})\exp(\frac{-\eta_1}{v_q}(1-\frac{2}{3}\frac{w}{(v_{go}-\eta)}-\frac{1}{9}\frac{w^2}{(v_{go}-\eta)^2}))$$

En réorganisant les termes :

$$=1+\exp(\frac{(\eta-\eta_1)}{v_q})\exp(\frac{w}{v_q}(1+\frac{2}{3}\frac{\eta_1}{(v_{go}-\eta)})+\frac{1}{9v_q}\frac{\eta_1 w^2}{(v_{go}-\eta)^2})$$

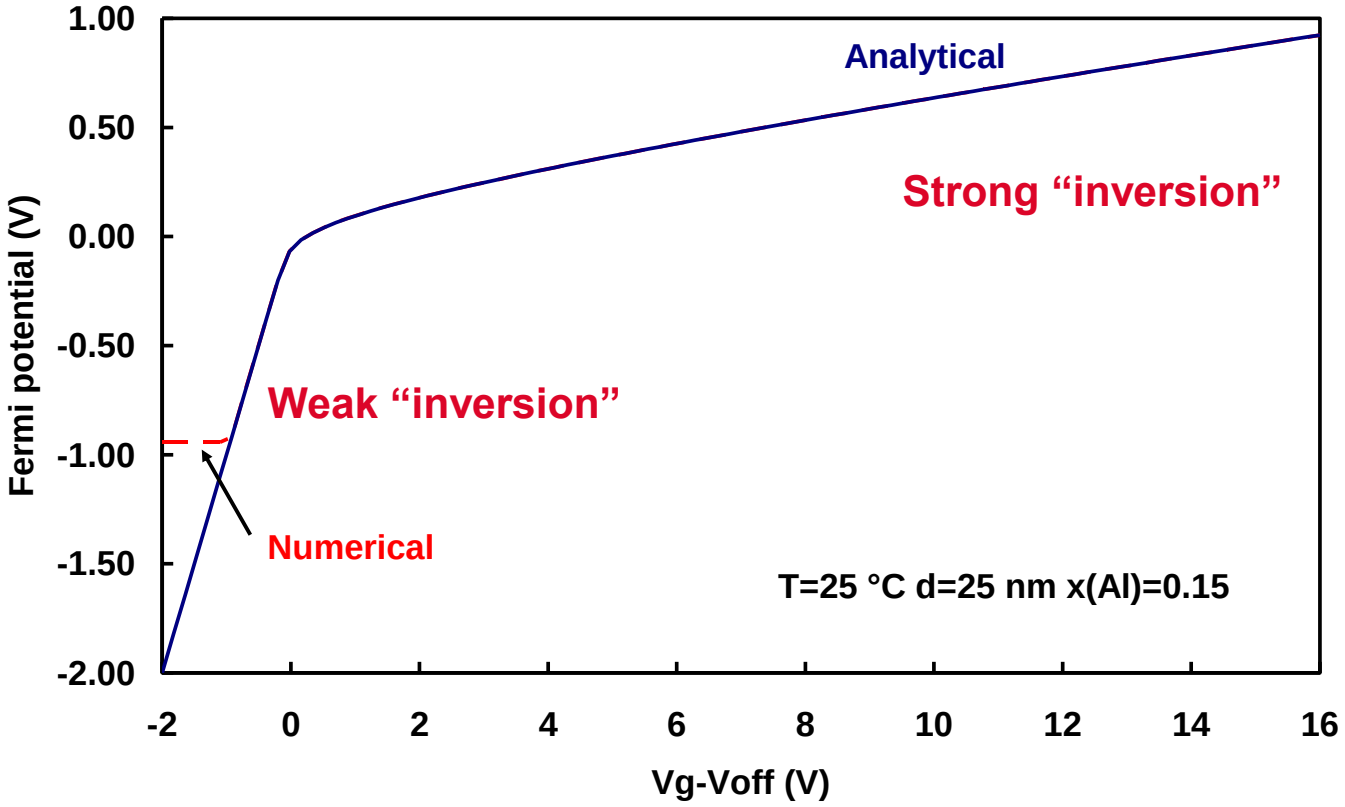
On simplifie cette expression en posant $e_1 = \exp((\eta-\eta_1)/v_q)$ et $s_1 = -(2/3)(\eta_1/(v_{go}-\eta))$:

$$=1+e_1\exp(\frac{w}{v_q}(1-s_1))\exp(\frac{1}{9v_q}\frac{\eta_1 w^2}{(v_{go}-\eta)^2})$$

On recommence notre étape de développement limité des termes $\exp(\frac{w}{v_q}(1-s_1))$ et $\exp(\frac{1}{9v_q}\frac{\eta_1 w^2}{(v_{go}-\eta)^2})$ à l'ordre 2 et en négligeant les termes d'ordre

- **We obtain different analytical expressions than Cheng'11: "A Surface-Based Compact Model for AlGaN/GaN MODFETs"**
- **Our expressions are valid for very high Vds (1kV)**

Comparison of Numerical & Analytical E_F calculation



- Numerical and analytical values of E_F are in great agreement
- Numerical calculation failed in very weak "inversion" as the triangular potential well assumption is no more valid

Velocity saturation and mobility model

- **Electron drift velocity and negative differential mobility in III-V semiconductors**
- **Much more simpler mobility model chosen in HSP:**

$$v_{drift}(E_L) = \frac{\mu_0 . E_L + v_{sat}\left(\frac{E_L}{E_c}\right)^{n_1}}{1+\left(\frac{E_L}{E_c}\right)+n_2\left(\frac{E_L}{E_c}\right)^{n_3}}$$

$$v_{drift}(E_L) = v_{sat}\frac{\frac{|E_L|}{E_c}}{\left[1+\left(\frac{|E_L|}{E_c}\right)^{\alpha}\right]^{\frac{1}{\alpha}}} = \mu_{LF}(E_T)\frac{|E_L|}{1+\left(\frac{|E_L|}{E_c}\right)} \quad for\ \alpha = 1$$

$$P(T) = P_0\left(a + bT + cT^2\right)$$

$$with\ P = v_{sat}, E_c, n_1, n_2, n_3$$

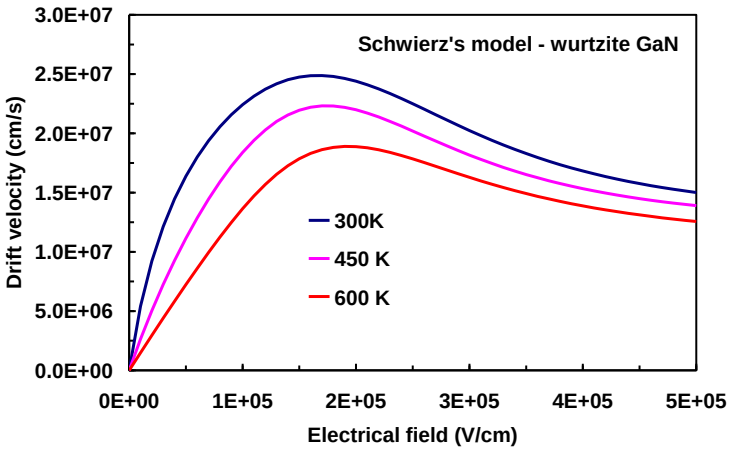
$$\mu_{LF}(E_T) = \frac{\mu_0}{1+\alpha|E_T|+\beta E_T^2}$$

$E_{Lateral}$

$E_{Transverse}$

$$\varepsilon_{GaN} . E_T = \varepsilon_{AlGaN} . \frac{(Vg - V_{off} - \Phi_{sm})}{d}$$

From Gauss theorem at AlGaN/GaN interface



Velocity in bulk wurtzite (hexagonal) GaN

Self-Heating Effect (SHE) modeling

- **Thermal conductivity** → $\kappa(T) = \kappa(T_{ref})\left(\frac{T}{T_{ref}}\right)^{KEX}$

  GaAs: KEX=-1.25
  Si: KEX=-1.3
  GaN: KEX=-1.4
  SiC: KEX=-1.5

- **3 SHE models (SHEMOD)**
  - **0 - No SHE**
  - **1 - Constant Rth, no heat dissipation through substrate**
  - **2 - With heat diffusion through substrate (thickness t_{sub}) and backside held at constant temperature T_0 (Canfield'90)**
- **Iterative calculation of drain current (SHEMOD=2)**

T, Par(T), Id, P_{diss} → $\Delta T = T_0 \frac{1-\left(1-\frac{P_{diss}}{4P_0}\right)^4}{\left(1-\frac{P_{diss}}{4P_0}\right)^4}$ → **$T=T_0+\Delta T$** → **Id'**

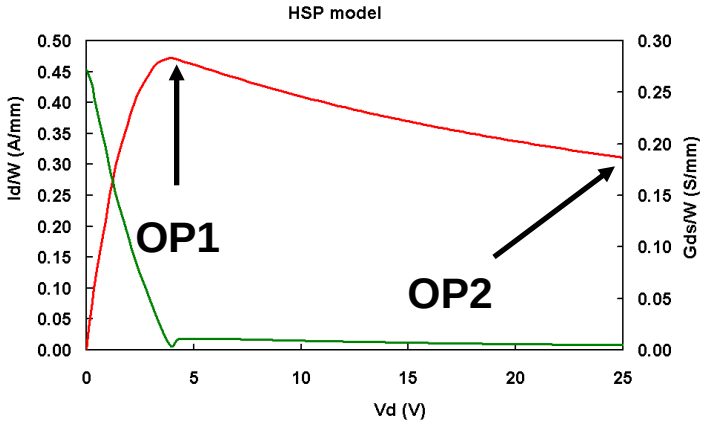
$$P_0 = \frac{\pi \kappa(T_0) W T_0}{Ln\left(\frac{8t_{sub}}{\pi \alpha L}\right)}$$

α ≤ 1: effective transistor length where heat dissipation occurs (Royet'00)

If $\Delta Id/Id < 10^{-6}$ exit loop

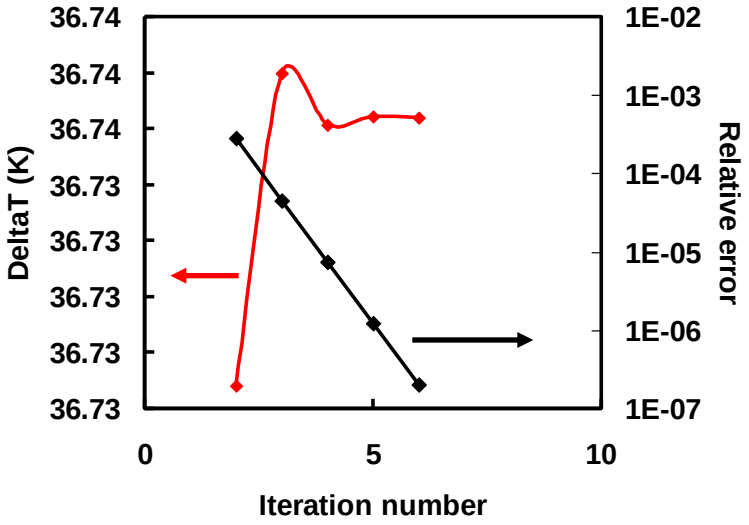
SHE: example of convergence

W=75 µm
L=1 µm
Vg=1 V
Temp=25 °C

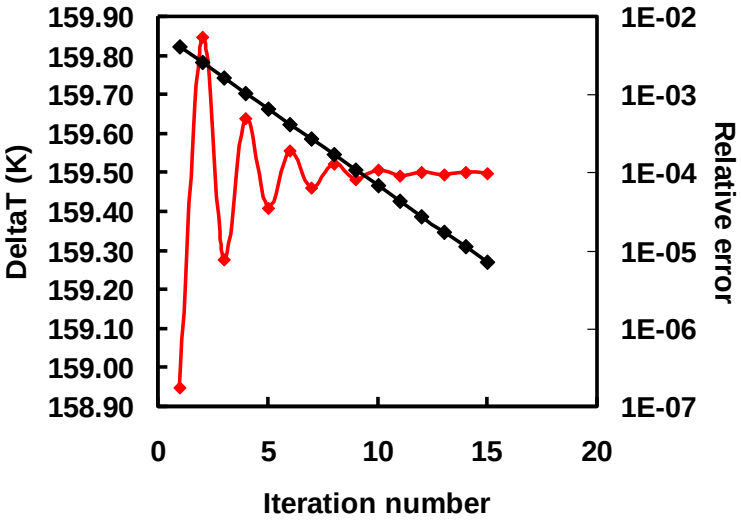


SHE_MOD=2
α=1
κ=150 W.m^{-1}.K^{-1} (Si)
KEX=-1.3
Tsub=400 µm
T_0=25 °C

OP1: 5 V, 35 mA, 0.17 W



OP2: 25 V, 23 mA, 0.58 W



Doping of AlGaN by Silicon ion implantation

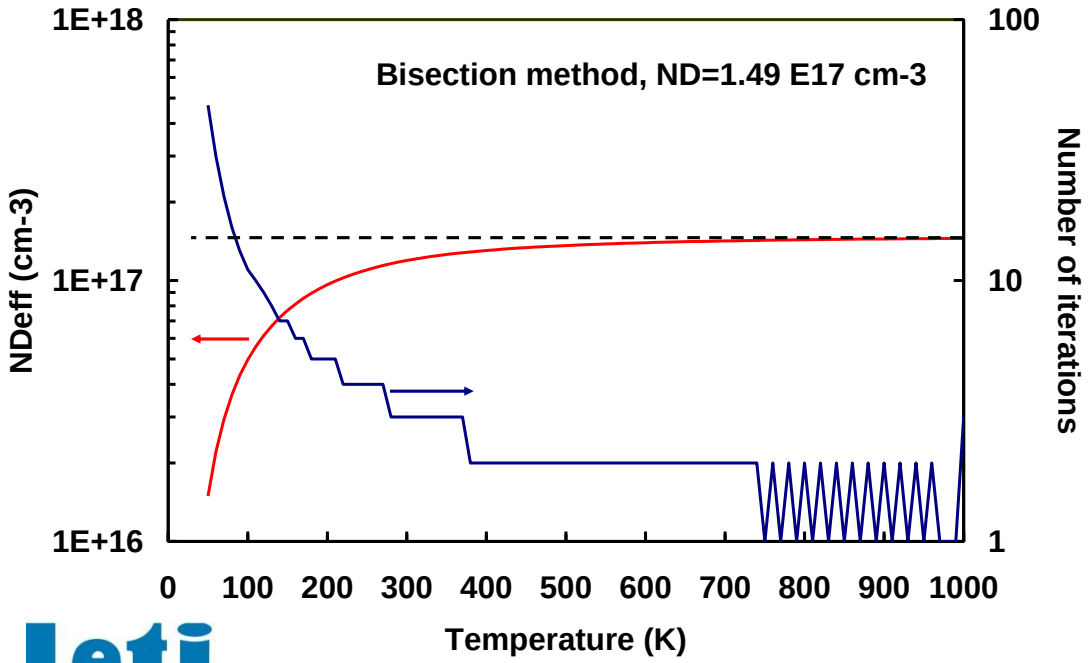
- Si substitutes for Ga in the lattice and acts as a donor
- Ionization of deep levels is incomplete at RT in refractory materials
- Two activation energies: ΔE_{D1}=12-17 meV, ΔE_{D2}=32-77 meV (Götz'96, GaN MOCVD films)
- Activation efficiency is function of implant temperature (Irokawa 2006): ~ 50 % at RT implantation
- Charge neutrality equation to be solved:

$$n(T) = \sum_{i=1}^{n} \frac{N_{Di}}{1 + \frac{g_i\, n(T)}{N_C(T)} \exp\left(\frac{\Delta E_{Di}}{kT}\right)} - N_A$$

n: Effective donor concentration
i: Index of donor
g: Degeneracy (g=2)
N_C: Density of states in CB
N_D: Donor concentration
ΔE_D: Donor activation energy
N_A: Conc. of compensing acceptors

Silicon donors in GaN

- Charge neutrality equation solved by the bisection method
- ΔE_{D1}=15 meV, ΔE_{D2}=37 meV (Götz'96, GaN MOCVD films)
- N_{D1}=1.1 10^{17} cm^{-3}, N_{D2}=3.9 10^{16} cm^{-3}, N_A=0, g_1=g_2=2, N_C=4.3 10^{14} $T^{1.5}$ cm^{-3} $K^{-1.5}$
- Three options in HSP (NDMOD):
  - 0: No partial ionization
  - 1: Partial ionization only during temperature modeling
  - 2: Partial ionization during temperature modeling and self-heating



NDeff / ND=80 % at RT (activation efficiency=100 %)

Ion implantation of Si in AlGaN: activation efficiency ≤ 50 % depending on implant temperature (Irokawa'06)

Calculation of drain current in the HSP model

- Drain current calculation like in the silicon Surface-Potential (SP) model (G. Gildenblat'02) following Cheng's work (2011)
- Calculation of $\Phi_{ss} = E_F + V_s$ (source) and $\Phi_{sd} = E_F + V_d$ (drain)
- Drain current proportional to $\Phi = \Phi_{sd} - \Phi_{ss}$
- Use of the approach of symmetric linearization introduced in SP
- Use of $\Phi_{sm} = 0.5 * (\Phi_{ss} + \Phi_{sd})$, the SP midpoint for symmetry considerations (see Gummel symmetry tests)
- Our model includes:
  - 1 - Parameters temperature and x_{Al} dependency
  - 2 - DIBL effect (V_{off} shift with V_{ds} and L)
  - 3 - Velocity saturation and channel length modulation (CLM)
  - 4 - Self-heating via an iterative method
  - 5 - Incomplete donor ionization via bisection method
  - 6 - Access resistances (Rs, Rd)

$$I_{ds} = \beta\, \mu_{LF}\, \frac{\left(V_{gs} - V_{off} + V_t - \Phi_{sm}\right)\Phi}{r_L + \delta_0\, \Phi / V_c}$$

HSP intrinsic charge model

- Importance of charge conservation in circuit simulation
- Calculation of Q_g
- Source and drain charges evaluated using the Ward-Dutton partitioning scheme
- If needed, capacitances will be calculated as derivatives of the terminal charges: $C_{ij}=-dQ_i/dV_j$ $(i\neq j)$, $C_{ii}=dQ_i/dV_i$ $(i=j)$
- 9 transcapacitances, 6 are independent due to charge conservation: $Qg + Qs + Qd = 0$

HSP model parameter list (1/2)

Setup parameters:

- DATAMOD AlGaN material data (Ambacher: 0, Yu: 1)
- VOFFMOD Set (0) or calculated (1) offset voltage
- VOFF Offset voltage

HEMT parameters:

- DD N-doped AlGaN layer thickness
- DI Undoped AlGaN layer thickness
- XAL Al content in $Al_xGa_{1-x}N$

AlGaN doping:

- NDMOD Donor partial ionization (0-1-2)
- ND Donor concentration (NDMOD=0)
- G1 Degeneracy of the 1st donor level
- G2 Degeneracy of the 2nd donor level
- ED1 1st donor energy level
- ED2 2nd donor energy level
- ND1 1st donor concentration
- ND2 2nd donor concentration
- NA Acceptor compensing concentration
- AEFF Ion implantation activation efficiency

Geometrical parameters:

- L Gate length
- W Gate width
- DL Gate length offset
- DW Gate width offset

Mobility:

- MU0 Low field mobility
- P1 1st mobility attenuation parameter
- P2 2nd mobility attenuation parameter

Velocity Saturation & CLM:

- EC Critical electrical field
- UA VS parameter
- PVS VS parameter

DIBL effect:

- DIBL1 DIBL 1st parameter (Vds)
- DIBL2 DIBL 2nd parameter (Length)

HSP model parameter list (2/2)

Self-heating effect:

- SHEMOD Self-heating mode (0-1-2-3)
- RTH Thermal resistance (SHEMOD=1)
- REX Thermal resistance temp. coeff.
- CTH Thermal capacitance
- TSUB Substrate thickness (SHEMOD=2-3)
- ALPHA Fraction of channel length for power dissipation (SHEMOD=3)
- KAPPA Substrate thermal conductivity
- KEX Thermal conductivity temp. coeff.

Access resistances:

- RS Source resistance
- RD Drain resistance

Temperature effects:

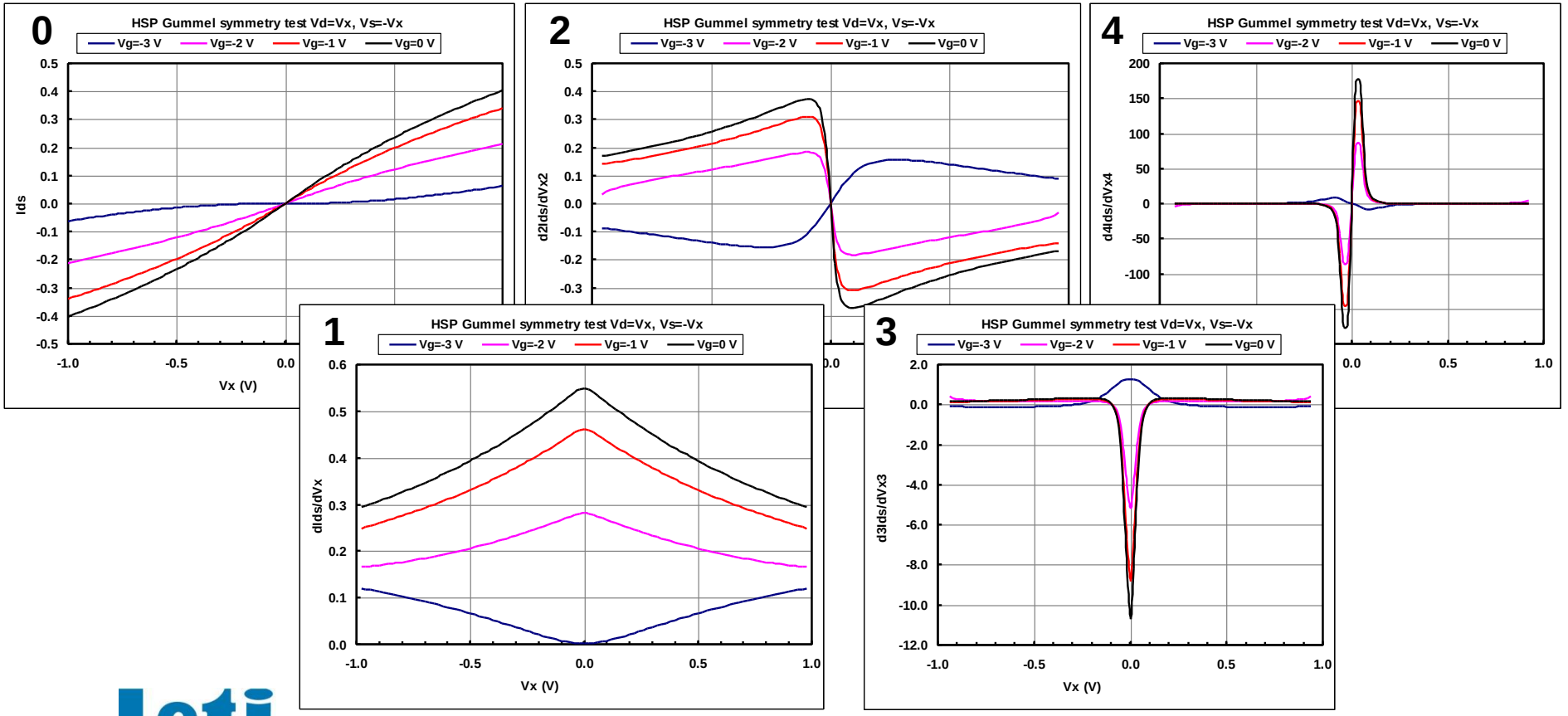
- TNOM Nominal temperature
- TCV VOFF temp. coeff.
- MUEX Mobility temp. coeff.
- ECEX EC temp. coeff.
- TR1 Resistance 1st temp. coeff.
- TR2 Resistance 2nd temp. coeff.

Overlap & fringing capacitance:

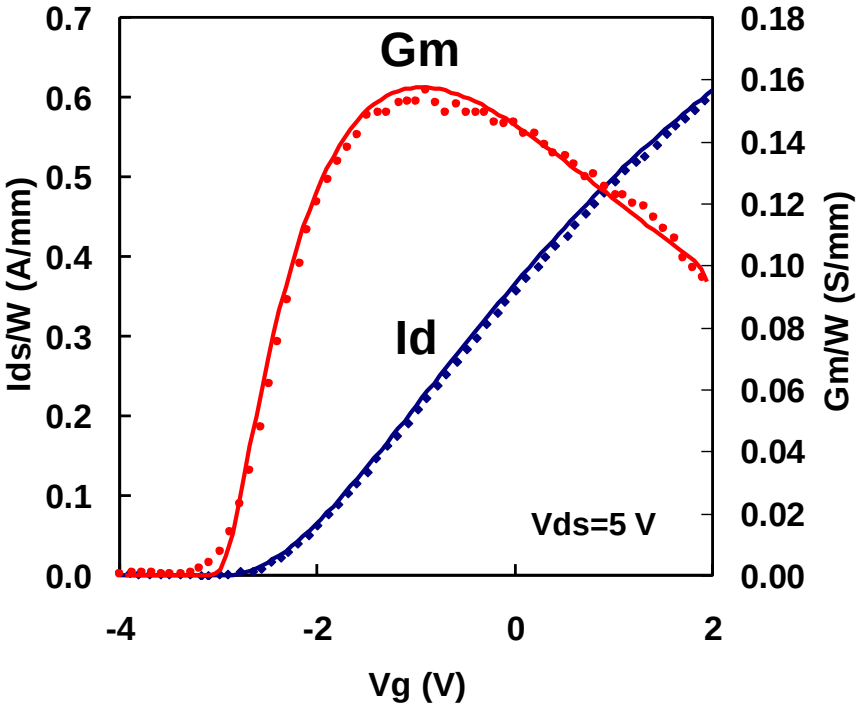
- COV Overlap cap.

Results: Gummel symmetry tests (GST)

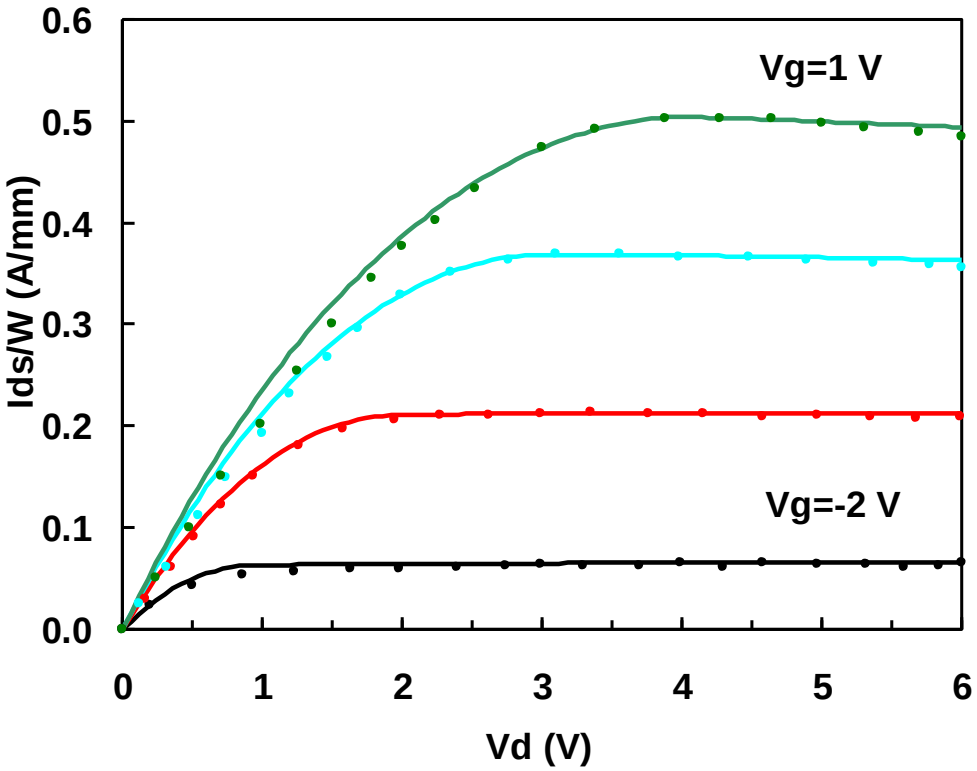
The drain current Id an odd function of V_x. Consequently, all odd order derivatives of $Id(V_x)$ with respect to V_x should be continuous at V_x=0, and all even order derivatives should be equal to zero at V_x=0



Results: Parameter extraction

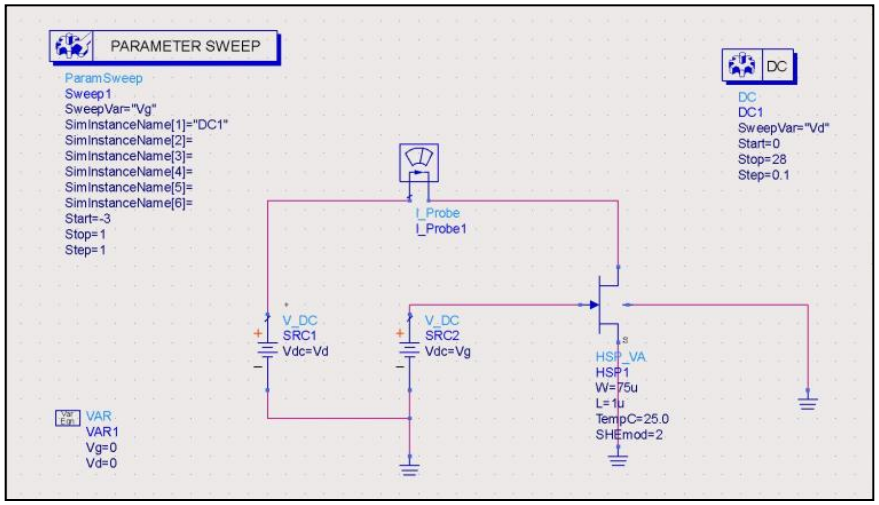


Experimental data from Wu'97

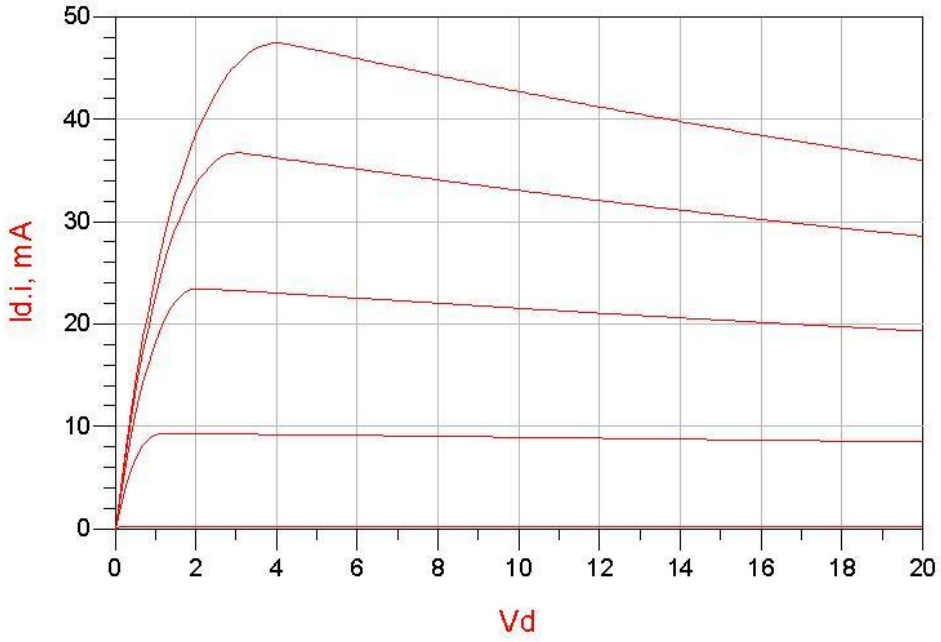


Results: DC current and self-heating

Verilog-A code + ADS simulation



L=1 µm and W=75 µm



Summary and conclusions

- HSP: a new approach and attempt for power devices modeling
- Physical approach (temperature, Al content, band structure, SP & PZ polarizations, layer thicknesses, doping, incomplete donor activation, heat diffusion in substrate, …)
- SP approach chosen for continuity of “inversion” charge
- Interesting tool for technological development (x_{Al}, Ga- or N-face, doping, layers thicknesses)
- This physical approach allows to estimate the impact of technological variations on electrical properties (variability)
- Further research efforts to improve the core model:
  e.g. SHE algorithm convergence for very high temperature increase ($\Delta T>300$ °C), Schottky gate current, impact of surface traps, …
- Implementation using Verilog-A and ADS simulator from Agilent

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