Compact modeling for GaN HEMT devices

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NANYANG
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**COMPACT MODELING FOR
GaN HEMT DEVICES**

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**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

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ABSTRACT

This thesis presents a compact model developed for generic High Electron Mobility Transistors (HEMTs). The model is based on unified regional modeling (URM) of the 2-dimensional electron gas (2-DEG) charge density, including the two lowest sub-bands of the triangular well in the strong inversion region, and extending to the moderate inversion and subthreshold regions in a single-piece formulation. The 2-DEG charge density model is adopted in the surface-potential-based current/charge model for conventional bulk MOSFETs, which makes it compatible and scalable for future III-V/Si co-integrated technologies. HEMT-specific features are also included, such as nonlinear source/drain access resistances, self-heating, and parallel-channel effects.

Apart from dc current/charge modeling, a comprehensive scalable trap-charge model for the dc and pulsed I–V modeling is also developed for GaN-based HEMTs, which suffer from current-collapse effects. A surface-potential-based model is proposed for interface traps, which is then adapted to the current model for the dc trap modeling. For the pulsed I–V modeling, a semiempirical approach is used for gate-lag and drain-lag conditions. The trap-charge model captures the effects of gate and drain quiescent biases as well as the stress time, and is validated with both TCAD and measurement data. The final model is coded in Verilog-A and compared with transient simulations from TCAD, demonstrating gate-lag effects under switching operations. The methodologies presented in this thesis provide a broad platform for designing next generation III-V on Si co-integrated ultra-large scale integration systems for high-frequency applications.

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LIST OF SYMBOLS

The following is list of symbols used in the text.

A	Contact area for Thermionic emission current equation (cm^2).
A^*	Effective Richardson constant ($\text{A}/\text{cm}^2\text{K}^2$).
a	Constant used in surface potential model ($\text{V}^{-1/3}$).
a_0	Intermediate variable in V_g - n_s solution (N.A).
a_1	Intermediate variable in V_g - n_s solution (N.A).
$\bar{A}_b$	Average body factor term (N.A).
A_f	Intermediate variable in V_g - n_s solution (N.A).
b	Constant used in surface potential model ($\text{V}^{2/3}$).
B_f	Intermediate variable in V_g - n_s solution (N.A).
C	Constant used in Poole-Frenkel Current ($\text{A}/\text{V}\cdot\text{cm}$).
C_d	Effective capacitance (per unit area) between the gate and 2-DEG (F/cm^2).
$\tilde{C}_d$	Effective capacitance C_d (per unit area) normalized to $q \cdot D$ (N.A).
C_f	Intermediate variable in V_g - n_s solution (N.A).
C_g	Total series capacitance of oxide and AlGaN barrier (F/cm^2).
C_{gg}	Total gate capacitance for GaN HEMT (F/cm^2).
C_{ij}	i - j Capacitance, both i and j can be any of the drain, gate or source terminal (F/cm^2).
C_{it}	Capacitance associated with a trap centre in conductance method (F/cm^2).
C_{K1}, C_{K2}	Intermediate variable in 2-T capacitance model (N.A).
C_m	Measured capacitance for conductance method (F/cm^2).
c_n	Constant associated with Airy function for n th energy state (N.A).
C_{ox}	Oxide capacitance for MIS-HEMT (F/cm^2).
$c_{ns} (c_{ps})$	Capture constant for electrons (holes) ($\text{cm}^{-1} \cdot \text{s}^{-1}$).
$c_{c,n,j}$	Capture coefficient for electrons for j^{th} trap level ($\text{cm}^{-1} \cdot \text{s}^{-1}$).
C_S	GaN capacitance per unit area (F/cm^2).
C_P	Equivalent parallel capacitance per unit area for conductance method (F/cm^2).
D	Density of states of the 2-DEG associated with a single quantized energy level ($\text{m}^{-2} \cdot \text{V}^{-1}$).
d	AlGaN barrier thickness (cm).
D_{it}	Interfaces trap density per energy ($\text{cm}^{-2} \text{eV}^{-1}$).
D_{eff}	Effective trap energy level reference to Fermi level (eV).
D_j	Trap energy reference to Fermi level for j^{th} trap level (eV).
E	Total energy in P-S equation (eV).
e	Spacer layer thickness (cm).
E_0	First bound energy state (eV).
E_1	Second bound energy band (eV).
E_A	Trap activation energy reference to bottom of the CB (eV).
$E_{A,j}$	Trap activation energy reference to bottom of the CB for the j^{th} trap level (eV).
E_f, E_{f1}	Position of Fermi level w.r.t bottom of conduction band (eV).
E_b	Effective electric field in the AlGaN barrier (V/cm).

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E_c	Conduction Band energy level (eV).
E_{eff}	Effective transverse field (V/cm).
$E_{f,\text{eff}}$	Effective 2DEG Fermi potential when GaN doping is considered (eV).
$E_{f,\text{str}}$	Strong-inversion regional E_f solution (eV).
$E_{f,\text{mod}}$	Moderate-inversion regional E_f solution (eV).
$E_{f,\text{sub}}$	Subthreshold regional E_f solution (eV).
$E_{f,\text{act}}$	Active region E_f solution connecting strong- and moderate-inversion region (eV).
$E_{f,\text{exact}}$	Exact E_f solution from P-S solution (eV).
E_{f1}	Alternative E_f solution when GaN doping is considered (eV).
$E_{f,\text{subACT}}$	Effective Subthreshold regional E_f solution when GaN doping is considered (eV).
$E_{f,\text{sf}}$	Unified surface Fermi Potential for the second channel when GaN doping is considered (eV).
$E_{f,\text{ss}}$	Saturated 2DEG E_f solution when GaN doping is considered for high gate bias (eV).
E_g	Energy band-gap of GaN buffer (eV).
E_i	Intrinsic Fermi level (eV).
E_k	Eigen energy (eV).
e_n	Emission rate (s^{-1}).
$e_{n,A,\text{eff}}$	Effective emission rate (s^{-1}).
$e_{n,A,j}$	Electron emission rates for j^{th} energy level for acceptor traps (s^{-1}).
E_n	Energy state of n^{th} state (eV).
$e_{\text{ns}} (e_{\text{ps}})$	Electron (hole) emission rates (s^{-1}).
E_o	Characteristic energy (eV).
E_T	Interface-trap level referenced to the intrinsic Fermi level (eV).
E_{T0}	Zero-field ionization energy (eV).
E_{sat}	Electric field at velocity saturation (V/cm).
$E_{\text{sat},c}$	Saturated electric field for source/drain node ($c=s/d$) (V/cm).
$E_{\text{sf},\text{act}}$	Surface Fermi Potential in the active region for the second channel when GaN doping is considered (eV).
$E_{\text{sf},\text{acteff}}$	Effective surface Fermi Potential in the active region when GaN doping is considered (eV).
$E_{\text{sf},\text{sub}}$	Surface Fermi Potential for the second channel in the subthreshold region when GaN doping is considered (eV).
$E_{t,A,j}$	j^{th} Acceptor trap energy level (eV) .
E_y	Lateral electric field along the channel (V/cm).
F	Electric field (V/cm).
f_T	Cut-off frequency (Hz).
$F_{t,A}$	Probability of ionization for acceptor traps (N.A).
$F_{t,A,j}$	Probability of ionization for j^{th} energy level for acceptor traps (N.A).
G	Intermediate variable in MTE model (N.A).
G_m	Measured conductance per unit area (S/cm^2).
g_m	Transconductance (S).
G_P	Equivalent parallel conductance per unit area (S/cm^2).
G_t	Equivalent tunnel conductance per unit area related to leakage current (S/cm^2).

List of Symbols

$\overline{g_{vo}}$	Average channel length modulation term (NA).
$g_{vo,d}$	Channel length modulation gain factor term at drain side (NA).
$g_{vo,s}$	Channel length modulation gain factor term at source side (NA).
H	Intermediate variable for charge model (V).
h_d, h_s	Intermediate variable for CLM model (N.A).
$\hbar$	Reduced Planck's constant (J.s).
I_0	Intermediate variable in thermionic emission current model (A).
I_{ds}	Drain-Source current (A).
I_{GR}	Generation-Recombination current (A).
I_R	Edge leakage current (A).
I_{TE}	Thermionic emission current (A).
j	Tuning parameter ranging between 0 and 1 (N.A).
J_{PF}	Current density corresponding to PF emission (A/cm ²).
J_T	Saturated tunneling current density (A/cm ²).
J_{TAT}	Trap assisted tunneling current (A/cm ²).
k	Boltzmann constant (J/K).
L_{eff}	Effective channel length (cm).
L_g	Gate drawn length (cm).
L_{gs}	Gate to source access region length (cm).
L_{gd}	Gate to drain access region length (cm).
m^*	Effective mass (Kg).
m	Total number of acceptor-like trap levels in the energy band-gap (N.A).
N_a	GaN buffer doping (cm ⁻³).
N_b	Doping concentration of the AlGaN barrier layer (cm ⁻³).
N_c	Conduction band density of states (cm ⁻³).
N_D	Ionized donor concentration (cm ⁻³).
n	Electron concentration (cm ⁻³).
n_i	Intrinsic carrier concentration (cm ⁻³).
n_k	Electron occupation for each state (N.A).
n_s	2DEG density (cm ⁻²).
$n_{s,0}, n_{s,1}$	Intermediate variable in Fermi potential model (cm ⁻²).
N_t	Trap density (cm ⁻²).
$N_{t,eff}$	Effective trap density (cm ⁻²).
n_t	Trapped 2DEG charge density (cm ⁻²).
N_{tr}	Recombination centre concentration (cm ⁻²).
$N_{t,A}$	Ionized acceptor trap density (cm ⁻²).
$N_{t,j}$	Trap density for the j^{th} trap energy (cm ⁻²).
$N_{t,A,j}$	Ionized acceptor trap density for the j^{th} trap energy (cm ⁻²).
$N_{t,A,eff}$	Effective ionized acceptor density (cm ⁻²).
p	Hole concentration (cm ⁻³).
q	Electronic charge (C).
Q_b	Bulk-charge per unit area (C/cm ²).
Q_d	Drain-charge per unit area (C/cm ²).
Q_g	Gate-charge per unit area (C/cm ²).
Q_i	Inversion-charge per unit area (C/cm ²).
q_i	Inversion-charge normalized to capacitance (V).
Q_{nT}	Effective trap charge density (C/cm ²).

List of Symbols

$\overline{Q_{nT}}$	Average trap charge density (C/cm ²).
$Q_{nT,deff}$	Effective trap charge density at drain side (C/cm ²).
$Q_{nT,seff}$	Effective trap charge density at drain side (C/cm ²).
Q_s	Source-charge per unit area (C/ cm ²).
Q_t	Total charge (per unit area) (C/ cm ²).
R_d	Drain access region resistance (Ω).
$R_{DS,ON}$	Dynamic on-resistance (Ω).
r_{ic}	Intrinsic channel resistance component at source/drain end (c=s/d) (Ω).
R_{it}	Resistance associated with a trap centre in conductance method (Ω /cm ²).
r_{out}	Output resistance of HEMT (Ω).
R_S	Series resistance in gate leakage model (Ω).
R_s	Source access region resistance (Ω).
R_{sh}	Shunt resistance in edge leakage current (Ω).
R_{th}	Thermal resistance (K/A).
T	Temperature (K).
T_0	Room temperature (K).
T_{cap}	Thickness of GaN cap (cm).
T_{ox}	Thickness of insulator (cm).
T_{off}	Stress time for pulsed I-V measurements (s).
V	Potential energy (eV).
N	Fitting parameter in mobility model (N.A).
v_0	Two-region piecewise velocity model (cm/s).
$V_{Aeff,d}$	Effective Early voltage at drain side (V).
$V_{Aeff,s}$	Effective Early voltage at source side (V).
$V_{bi,s}$	Drain built-in potential (V).
$V_{bi,d}$	Source built-in potential (V).
V_c	Channel voltage (V).
$V_{c,eff}$	Effective channel voltage (V).
V_d	Ground referenced drain voltage (V).
V_{d0}	Drain voltage for linear region I_{ds} calculation (50mV).
V_{di}	Internal drain voltage for subcircuit model (V).
V_{dd}	Supply voltage (V).
$V_{d,eff}$	Effective drain voltage (V).
V_{dq}	Drain quiescent bias (V).
V_{ds}	Drain-source voltage (V).
$V_{ds,eff}$	Effective drain-source voltage (V).
$V_{d,sat}$	Ground referenced drain saturated voltage (V).
$V_{ds,sat}$	Drain-source saturation voltage (V).
V_{FB}	Flat-band voltage (V).
V_g	Ground referenced gate voltage (V).
V_{gb}	Gate-bulk voltage (V).
V_{go}	V_{off} -shifted gate voltage (V).
V_{gq}	Gate quiescent bias (V).
$V_{g,CR}$	Critical gate voltage when $E_f = E_0$ (V).
$V_{go,act}$	Active region effective V_{off} -shifted gate voltage (V).
$V_{go,CR}$	V_{off} -shifted critical voltage (V).

List of Symbols

$V_{g,SUB}$	Subthreshold gate voltage when $E_f = 0$ (V).
$V_{gq,act}$	Effective gate quiescent bias (V).
$V_{go,SUB}$	V_{off} -shifted Subthreshold voltage (V).
$V_{gt,c}$	Normalized inversion charge at source/drain side ($c=s/d$) (V).
$\overline{V}_{gt}$	Average inversion charge normalized to the oxide capacitance (V).
V_{kink}	Kink voltage (V).
v_n	Thermal velocity of electrons (cm/s).
V_{off}	Cut-off voltage corresponding to 2DEG (V).
$V_{off2,}$	Cut-off voltage corresponding to second channel for MISHEMTs (V).
$V_{off,fnl}$	Final threshold voltage after trapping event (V).
V_{Qeff}	Intermediate variable in gate-lag model (V).
v_p	Thermal velocity of holes (cm/s).
V_s	Ground referenced source voltage (V).
V_{si}	Internal source voltage for subcircuit model (V).
$V_{s,eff}$	Effective source voltage (V).
$V_{s,sat}$	Ground referenced source saturated voltage (V).
V_{STEP}	Step function in gate-lag model (N.A).
v_{sat}	Saturated electron velocity (cm/s).
v_{sat1}	Length dependent velocity saturation parameter 1 (cm/s).
v_{sat2}	Length dependent velocity saturation parameter 2 (cm/s).
v_α	Length dependent velocity saturation parameter 3 (μm).
v_β	Length dependent velocity saturation parameter 4 (N.A).
$v_{satc}, v_{sats}, v_{satd}$	Access region saturation velocity, $c=s/d$ (source/drain) (cm/s).
V_t	Threshold Voltage (V).
v_{th}	Thermal voltage (V).
W	Width of the HEMT (cm).
W_d	Depletion width in the 2DEG channel (cm).
$X_{dm,c}$	Maximum depletion width at the source/drain end ($c=s/d$) (cm).
X_{dm}	Maximum depletion width (cm).
y_{min}	Minimum surface potential location along the channel (cm).
α	Smoothing parameter in strong-inversion surface potential model (N.A).
α_2	Smoothing parameter in surface potential model (V).
α_D	Fitting parameter for drain-lag model (N.A).
α_h	Fitting parameter in gate-lag model (V).
α_t	Linearity factor in gate-lag model (N.A).
α_{dibl}	Fitting parameters for DIBL model (N.A).
α_{Ts}, α_{Td}	Two fitting parameter to tune the effect of the corresponding traps at the source and drain side respectively (N.A).
β	Gain factor in drain current (AV^{-2}).
β_{PF}	Constant in Poole-Frenkel current equation ($V^{-1}cm^{-1}$).
Γ	Smoothing parameter for alternative E_f solution when GaN doping is considered (V).
γ_0	Constant related to lowest energy state in triangular quantum well
γ_I	Constant related to second energy state in triangular quantum well
γ_{sc}	Fitting parameter for short-channel-effects model (N.A).

List of Symbols

$\Delta\phi_s$	Surface potential difference (V).
ΔE_c	Conduction band offset at the hetero-interface (eV).
ΔE_f	Intermediate variable in Fermi potential model (V).
$\Delta\phi_{PF}$	Potential lowering in Poole-Frenkel Model (V).
ΔV_{off}	Threshold-voltage shift under electron trapping phenomena (V).
$\Delta V_{off,MAX}$	Maximum shift in the V_{off} under electron trapping phenomena (V).
ΔT	Increase in temperature for Self-heating effects (K)
δ_L	Fitting parameter for lateral field degradation (N.A).
δ_s	Smoothing parameter for effective voltage from linear to saturation (V).
δ_{s1}	Length dependent smoothing parameter coefficients 1 for smoothing parameter for effective voltage from linear to saturation (V).
δ_{s2}	Length dependent smoothing parameter coefficients 2 for smoothing parameter for effective voltage from linear to saturation (V).
δ_{s3}	Length dependent smoothing parameter coefficients 1 for smoothing parameter for effective voltage from linear to saturation (μm).
δ_{s4}	Length dependent smoothing parameter coefficients 1 for smoothing parameter for effective voltage from linear to saturation (N.A).
$\delta\phi_s$	Quasi 2-D potential lowering for short-channel-effects model (V).
$\delta\phi_{s,c}$	Quasi 2-D potential lowering at source (c=s) or drain (c=d) side for SCE model (V).
E	Smoothing parameter in surface potential model (V^2).
ε_1	Smoothing parameter in surface potential model (V^2).
ε_b	Permittivities of the AlGaN barrier layer (F/m).
ε_{ox}	Permittivities of the insulator layer (F/m).
ε_t	Smoothing parameter in gate-lag model (V^2).
ε_{tr}	Smoothing parameter in transient trap model (V^2).
ε_{uid}	Permittivities of GaN buffer (F/m).
ζ_b	Fitting parameters for bulk charge term in effective electric field (N.A).
ζ_n	Fitting parameters for inversion charge term in effective electric field (N.A).
η_{est}	Intermediate variable in Fermi potential model
n_F	Ideality factor in Thermionic emission leakage current model (N.A).
η_{sc}	Prefactor for quasi-2D solution for short-channel-effects model (N.A).
Θ	Intermediate variable in Fermi potential model (N.A).
$\kappa_{t,j}$	Proportionality factor in MTE model for j^{th} trap energy level (N.A).
λ_0	Intermediate variable in Fermi potential model (N.A).
λ_c	Fitting parameter for quasi-2D solution at source (c=s) or drain (c=d) side (cm).
$\mathcal{M}, \mathcal{M}_0, \mathcal{M}_1$	Intermediate variable in strong-inversion potential model (N.A).
M	Mobility in the channel ($cm^2/V\cdot s$).

List of Symbols

μ_0	Transverse field mobility ($\text{cm}^2/\text{V}\cdot\text{s}$).
$\mu_{0,c}$	Transverse field mobility at the source (c=s) or drain (c=d) ($\text{cm}^2/\text{V}\cdot\text{s}$).
μ_1	Mobility fitting parameters ($\text{cm}^2/\text{V}\cdot\text{s}$).
μ_2	Mobility fitting parameters ($\text{cm}^{5/3}/\text{V}^{2/3}\cdot\text{s}$).
μ_3	Mobility fitting parameters ($\text{cm}\cdot\text{s}$).
μ_{co}	Coulombic scattering ($\text{cm}^2/\text{V}\cdot\text{s}$).
μ_{ph}	Phonon scattering ($\text{cm}^2/\text{V}\cdot\text{s}$).
μ_{sr}	Surface roughness scattering ($\text{cm}^2/\text{V}\cdot\text{s}$).
μ_{rc}	Mobility in the extrinsic source (c=s) or drain (c=d) ($\text{cm}^2/\text{V}\cdot\text{s}$).
μ_{eff}	Effective channel mobility ($\text{cm}^2/\text{V}\cdot\text{s}$).
ξ_C	Fitting parameter in CLM model (N.A).
ξ_{rc}	Fitting parameter in source/drain (c=s/d) velocity saturation model (N.A).
ρ	Smoothing parameter in surface potential model (V).
σ	Polarization-induced charge density at the heterointerface (cm^{-2}).
σ_c	Capture cross-section for electrons or holes (cm^2).
$\sigma_{c,n,j}$	Capture cross-section for electrons of j^{th} trap energy level (cm^2).
σ_{eff}	Effective polarization charge density after trapping (cm^{-2}).
σ_m	Maximum trapped polarization charge density (cm^{-2}).
$\sigma_n (\sigma_p)$	Capture cross-section for electron (holes) (cm^2).
σ_o	Polarization charge density with no trapping effect (cm^{-2}).
τ_C	Capture time constant (s).
τ_E	Emission time constant (s).
$\tau_{e,\text{eff}}$	Effective emission time constant under MTE model (s).
τ_{it}	Interface trap time constant (s).
τ_{rc}	Effective carrier lifetime (s).
Υ	Body factor term when GaN doping is considered ($\text{V}^{1/2}$).
Φ_{MB}	Metal-to-insulator barrier height (eV).
Φ_{SB}	Insulator-to-GaN cap barrier height (eV).
Φ_{B}	Zero-bias barrier height (eV).
$\phi_{c,\text{eff}}$	Effective surface potential with c = s/d for source/drain (S/D) (V).
ϕ_F	Difference between the Fermi level E_F and the intrinsic potential E_i (V).
ϕ_s	Surface potential (V).
ϕ_{s1}	Surface potential referenced to the Fermi level in the body (V).
ϕ_{sa}	Actual surface potential referenced to the conduction band E_c in the body (V).
$\phi_{\text{saeff},c}$	Effective actual surface potential referenced to the conduction band E_c in the body (V) at the source (c=s) or drain (c=d) end (V).
$\phi_{s,d}$	Surface potential at drain end (V).
$\phi_{s,s}$	Surface potential at source end (V).
ϕ_s	Average surface potential between source and drain end (V).
ϕ_{sub}	Subthreshold surface potential regional solution (V).
ϕ_t	Barrier height for the electron emission from the trap state (V).
ψ	Electron wave function (NA).
ω	Radial frequency (Hz).
ω_s	Intermediate variable in Fermi potential model ($\text{V}^{-2/3}$).

List of Acronyms

LIST OF ACRONYMS

Acronyms	Description
2DEG	2 Dimensional e lectron g as
AC	A lternative c urrent
AlGaN	A luminium G allium N itride
BSIM	B erkeley short-channel i nsulated-gate field-effect transistor m odel
CC	C urrent c ollapse
CFOM	C ombined f igure of m erit
CLM	C hannel l ength m odulation
CM	C ompact m odel
CMOS	C omplementary m etal o xide semiconductor
DC	D irect c urrent
DD	D rift- d iffusion
DG	D ouble g ate
DIBL	D rain induce b arrier lowering
EKV	E nz- K rummenacher- V ittoz Model
FDM	F inite d ifference m ethod
GR	G eneration r ecombination
GST	G ummel symmetry t est
HBT	H etero- j unction b ipolar transistors
HEMTs	H igh electron m obility transistors
HF	H igh frequency
HFET	H eterostructure field-effect transistor
HiSIM	H iroshima-university S TARC insulated-gate field-effect transistor m odel
HP	H igh p ower
LEDs	L ight emitting d iodes
MIS-HEMTs	M etal-insulator-semiconductor h igh electron m obility transistors
MODFET	M odulation d oped field-effect transistor
MOSFET	M etal- o xide-semiconductor- f ield-effect transistor
MTE	M ulti t rap e nergy
N.A	N ot a pplicable
NMOS	N -channel M OSFET
NR	N ewton- R aphson
PD	P artially- d epleted
PF	P oole F renkel emission
PS	P oisson- S chrodinger
PSP	P enn- S tate- P hilips Model
Quasi-2D	Q uasi- t wo- d imensional
RF	R adio- f requency
SCEs	S hort-channel e ffects
SHEs	S elf- h eating e ffects
Si	S ilicon
SOI	S ilicon- o n- i nsulator
SP	S urface p otential

List of Acronyms

STE	Single trap energy
TAT	Trap assisted tunneling
TCAD	Technology computer-aided design
TE	Thermionic emission
UID	Unintentionally doped
URM	Unified regional modeling
URSP	Unified regional surface potential
VO	Velocity overshoot
WKB	Wentzel-Kramers-Brillouin method
w.r.t	With respect to

Chapter 1: Introduction

1.1 An overview of GaN HEMT technology

Wireless communication (satellite communications, TV broadcasting, broadband wireless internet connection, transmitter base station amplifiers) and military applications (radars, missile seekers) require high output power at high frequencies [1, 2]. Growing needs for higher output power generation in case of radio-frequency (RF) and wider spectral range in Light Emitting Diodes (LEDs) require new semiconductor materials and device designs [3]. A variety of power amplifier technologies with different III-V materials of suitable band-gap such as GaAs (or GaAs/InGaP) hetero-junction bipolar transistors (HBT), SiC MESFETs, and GaN High Electron Mobility transistors (HEMTs) are available to technology developers [4-11]. Some of the material properties of various contenders are listed in Table 1.1. It is evident that GaN in comparison with the other material systems emerges as a better choice. Through meticulous research it has been recently shown that fully CMOS-based GaN processes are possible to achieve and is gaining a broad focus from the semiconductor research community [4, 5],[15,16].

TABLE I
PHYSICAL PROPERTIES OF VARIOUS SEMICONDUCTORS [1,4,5]

	Si (SiGe/Si)	GaAs (AlGaAs/ InGaAs)	InP (InAlAs/ InGaAs)	4H SiC	GaN (AlGaN/ GaN)	Diamond
Bandgap (eV)	1.1	1.42	1.35	3.26	3.49	5.45
Electron- mobility (cm²/Vs)	1500 (2800)	8500 (8000)	5400 (10000)	700	900 (>2000)	4000
Saturated (peak) Electron velocity (x10⁷cm/s)	1.0 (1.0)	1.0 (2.1)	1.0 (2.3)	2.0 (2.0)	1.5 (2.7)	2.8
2DEG sheet electron density (cm⁻²)	2x10¹²	<3x10¹²	<4x10¹²	N.A.	1-2x10¹³	NA
Critical breakdown field (MV/cm)	0.3	0.4	0.5	2.0	3.3	10
Thermal conductivity (W/cm-K)	1.5	0.5	0.7	4.5	>2.0	2.2

The Combined figure-of-merit (CFOM) for high-power, high-frequency, high-temperature applications makes GaN system a preferable choice. With a large band-gap of 3.49 eV, a breakdown field of 3.3×10^6 V/cm, electron mobility of $1350 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ and its ability of forming a 2 Dimensional Electron Gas (2DEG) at a heterojunction interface due to its spontaneous polarization properties, with a typical carrier density of $> 1 \times 10^{13} \text{ cm}^{-2}$ and high electron saturation velocities up to $2.5 \times 10^7 \text{ cm/s}$ has made GaN one of the best choices for usage in the high-power and high-frequency regime operation.

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HEMT, also known as heterostructure FET (HFET) or modulation-doped FET (MODFET) is a field-effect transistor incorporating a junction between two materials with different band gaps (i.e. a heterojunction) as the channel instead of a doped region (as is generally the case for MOSFET). HEMT devices are able to operate at higher frequencies than ordinary transistors, up to millimeter wave frequencies, and are used in high-frequency products such as cell phones, satellite television receivers, voltage converters, and radar equipment. To utilize all the advantages of GaN based HEMTs in our daily life, a strong focus is needed not only on fabrication but also on the device/circuit modeling and design. This is where the importance of device modeling comes into the picture.

1.2 Background of compact modeling

With aggressive scaling, the integration of millions of transistors and other passive devices on a single chip has become more challenging for process engineers [17]. Thus, the importance of device modeling in electronics industry has grown tremendously in the past few years. In today's market to meet the huge demand for electronics products, not only advancement in fabrication process is important, but compact and accurate device models are also critical for prediction of future device characteristic. In the most advanced technology, device model development necessitates the understanding on the device layout, fabrication, and physical operation to properly develop a compact model that is able to match real device electrical behaviours. The design house always aims to achieve a close match of the device models with measurement data.

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Technology computer aided design (TCAD) simulators provide a good physical insight of FET transport characteristics with accurate solutions of differential equations [18]. However, these simulators are not suitable for circuit designs because it is too computational demanding to run simulations of many transistors in a circuit, for which a compact model becomes extremely necessary. The bulk MOSFET compact model that was derived based on the Poisson equation and Gauss' law had been established by Pao-Sah in the mid 1960s [19]. The drain current was described as a double integral, in which the solution has to be obtained by numerical integration which is again not suitable for use in circuit simulation. With charge-sheet approximation, the double-integral equation for the drain current can be expressed as an explicit function of the surface potential [20] without losing much accuracy (1~2% error). The charge-sheet drain current model, however, still needs the surface potential solutions, which can be solved iteratively at the drain and source ends of the channel using the Pao-Sah input voltage equation [19].

Based on this (Pao-Sah) voltage equation, three different approaches to compact solutions have been developed over the years, namely, the threshold-voltage (V_t) based, surface potential (ϕ_s) based, and inversion-charge (Q_i) based. The classification of these different approaches was based on the intermediate variable (i.e., V_t , ϕ_s , or Q_i) used to derive the charge and current models. The first generation V_t based compact models have been popular due to simplicity of equations relating the input gate voltage and surface potential. The surface potential was assumed as a linear function of input gate-bulk voltage, V_{gb} when it is below V_t and constant above V_t , also referred to as the “pinned” surface potential model. The drain current model was obtained with a Taylor expansion

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at the source end from the charge-sheet drain current model, resulting in a very simple form with all the current and charges to be expressed as a function of V_t . This model has been implemented in the BSIM family [15,16] of models and MOS9. However, V_t based compact models suffer from the Gummel symmetry problems [23] due to its source referencing as well as discontinuities and accuracy problems in moderate inversion region.

The second approach based on surface potential requires iterative solution (such as in HiSIM) [24] or explicit (such as in SP) [17,18], which later was known as PSP after it merged with Philip's MOS 11 ϕ_s -based model. The terminal currents and charges were formulated based on the solution of the surface potential. The iterative approach was relatively slow in the initial days also leading to convergence problems and non-iterative approach cannot extend to accumulation region. However, with the newly developed iterative algorithms, the execution time for ϕ_s -based models has improved tremendously [24]. It is worth mentioning that ϕ_s -based models are becoming more popular due to its strong physical contents. Nonetheless, high accuracy of the surface-potential solution is required in the ϕ_s -based model to produce proper subthreshold (or weak inversion region) behaviour and correct trans-capacitance [27].

In the third approach (Q_i -based models), the surface potential was approximated from the voltage equation with a linear function of inversion charge density [28] in the inversion region. The terminal charges and currents are then formulated based on the solution of the charges. Examples of such models are the EKV model [29] and BSIM5 model [22].

1.3 Motivation of the thesis

Silicon technology has been the primary option for the semiconductor industry since 1960s, with MOSFETs being the key electronic devices. However, some specific applications like LEDs, Laser Diodes and RF devices require the use of compound semiconductors due to its high electron mobility and band-gap. HEMTs have the advantages of high mobility and low noise for high-frequency (HF) and high-power (HP) applications compared with conventional Silicon MOSFETs. Thus, a compact model (CM) that physically describes the behaviours in all operation regions of a generic HEMT device is highly demanded for the design of HEMT-based circuits.

However, the use of existing CMOS-based compact models for HEMT devices does not seem to be justified due to a completely different physics of the latter as a strong quantum mechanical effect is present [30]. In heterostructures, a sharp triangular quantum well is formed where the Boltzmann statistics is not fully valid [9,10]. A coupled Poisson-Schrodinger (P-S) approach offers a more accurate solution. Yet, the iterative and complex nature of the coupled solution is not suitable for circuit designers for which a more simplified explicit model is necessary. The core model in this thesis is based on the unified regional modeling (URM) approach which includes the short-channel effects (SCEs) and the self-heating effects (SHEs). The model will also be extended to metal-insulator-semiconductor (MIS)-HEMTs. The main motivation behind this work is to develop a compact current and charge model for generic HEMT devices that can be utilized for future generation III-V/Si co-integrated ULSI systems.

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A compact current and charge model is not sufficient for GaN HEMT based circuit design as traps play a bigger factor in determining the DC and Pulsed I - V characteristics. In this context, the DC-RF dispersion, otherwise known as the “current collapse” effect [12,13], has been a major concern among the process and design engineers. The DC data no longer represents the actual device performance at high frequency, whereby electron trapping/detrapping takes place. Thus, there is a genuine motivation to extend the current model so as to capture the trapping/detrapping effects. Based on the frequency of operation, circuit designers can use the pulsed I - V model to predict the DC-RF dispersion effects.

1.4 Objective of the thesis

The main objectives of this research are to:

- (a) Develop a scalable surface potential model for GaN HEMTs based on Poisson-Schrodinger solution and unified regional modeling approach.
- (b) Derive a compact drain current model that is simple and scalable with channel length as well as access region lengths.
- (c) Understand the different mechanisms of forward and reverse gate-leakage in GaN HEMTs.
- (d) Extend the current model to Metal-Insulator-Semiconductor (MIS)-HEMTs.
- (e) Understand the different types of trapping/detrapping phenomena in GaN HEMTs under DC as well as pulsed I - V conditions.

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- (f) Develop and implement the compact model exhibiting the electron capture/emission process in VERILOG-A environment.

1.5 Major contribution of the thesis

A detailed diagram showing the challenges in GaN HEMT modeling is shown in Fig. 1.1. The major contributions of this thesis are listed below:

- (a) Proposed a new unified regional surface potential (URSP) solution for AlGaIn/GaN HEMTs. Regional surface potentials are modeled for subthreshold, moderate- and strong-inversion regions. The moderate-inversion surface potential model solution based on *Lambert-W* function is one of the major focus of this work.
- (b) The surface potential model is extended to DC/AC modeling that is able to capture short-channel and self-heating effects. The model scales with gate length as well as source/drain access regions lengths. The effect of GaN buffer doping is incorporated in to the current model which affects the subthreshold slope at high drain bias due to the “thick body effects”. One of the major contribution of this work is to develop the unified surface potential model, that considers effect of buffer doping in subthreshold region, and Poisson-Schrodinger based solution in ON-state.
- (c) Apart from drain current modeling, gate leakage is also modeled in this work. The different transport mechanisms for gate leakage at different bias is studied and modeled, validated with measurement data for

Fig. 1.1: A detailed list of current challenges in GaN HEMT modeling and the corresponding contribution in this work

different temperatures. The effect of GaN buffer doping on the surface potential in the subthreshold region as well as the reverse gate leakage current is presented. It is shown that the increase of reverse gate leakage with negative gate-bias based on Poole-Frenkel emission can be explained if the effect of buffer doping is taken into consideration.

- (d) The current model is also extended to capture the “parallel channel” effects in Metal-Insulator-Semiconductor (MIS)-HEMTs at high gate-bias. Based on the surface potential solution of the second parallel

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channel, the second hump in transconductance is modelled and validated with numerical simulation.

- (e) The effect of traps on the DC characteristics is studied and a compact model able to capture the capture/emission process is presented. A new multi-trap energy model is proposed which takes in to account traps with different energy levels. Pulsed I - V characteristics are analysed and a gate-lag and gate/drain-lag model is proposed which captures the effect of gate and drain quiescent bias as well as the stress time.
- (f) Finally, the gate-lag model is implemented in VERILOG-A where the transient simulations are able to show the capture/emission process.

1.6 Organization of the thesis

This thesis is written in five chapters. Chapter one stated the motivations and objectives of this work.

Chapter two discusses the background of compact modeling methodologies that currently exist in DC/AC bulk-MOSFETs compact models. This is followed by a detailed discussion about how the URSP approach was extended for HEMT devices based on position of sub-bands in a quantum well. The compact model is physically derived based on the regional solution from coupled Poisson-Schrodinger solution with some approximations, which are then unified with interpolation functions for smooth higher order derivatives. The surface potential solutions are then used in the drain-current and charge models based on drift-diffusion (DD) formulation leading to a core model scalable over different channel lengths. The effects of source/drain access

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regions, self-heating and short-channel-effects are implemented as well to improve the validity of the proposed model. The effects of forward and reverse gate leakage in HEMTs as well as the formation of second parallel channel in MIS-HEMTs are also modeled.

Chapter three demonstrates the DC/AC model parameter extraction procedure for AlGaIn/GaN HEMTs. The compact model is verified using numerical simulations (TCAD). A step-by-step model parameter extraction is illustrated. The gate length as well the access region lengths are varied and have been used to verify the scalability of the model.

Chapter four provides a detailed study about the effect of traps on DC as well as Pulsed I - V characteristics. The first section of this chapter focuses on the DC trap model formulation and validation with TCAD data. Also, a new Multi-Trap Energy (MTE) model is proposed. The second part of this chapter explores the Pulsed I - V characteristics under various gate- and drain-lag conditions and presented a compact model that is able to simulate the capture/emission processes. In the last section, a transient drain current model with the gate-lag effects is presented and implemented in VERILOG-A environment.

Finally, chapter five summarizes and concludes the AC/DC HEMT modeling methodology with suggestions and recommendations for future investigations.

Chapter 2: Surface Potential Based I-V Model of HEMTs/MIS-HEMTs

2.1 Introduction to the URM approach

The core model presented in this thesis is based on the unified regional modeling (URM) approach. Previously, this approach was implemented for bulk MOSFETs and later extended to model future devices, such as strained-Si [33] and Double-Gate (DG) MOSFETs [27]. It provides a better physical geometry scaling for a given technology. The URM approach incorporates more physics [34] with the regional surface potential. It is derived from the input voltage equation in different regions of operation of MOSFETs, namely, accumulation, depletion, and strong inversion, depending on the gate-bulk bias (and channel doping concentration). Unlike the explicit ϕ_s approach which “glues” the pieces of surface potentials together, the unified regional surface potentials are “stitched” using interpolation/smoothing functions [9] to ensure the model continuity for all derivatives.

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To ensure the fulfilment of the Gummel Symmetry Test (GST) [18, 26], the drain current is carefully re-derived without the need for accurate surface potentials. Furthermore, a complete short-channel drain current model has also been demonstrated. Self-heating effect was incorporated which is observed in GaN HEMTs. The nonlinear source/drain access region resistance was modelled using sub-circuit approach based on the polarization charge and velocity saturation effects. This chapter discusses the development of a scalable model based on the URM approach for generic HEMTs with the help of numerical simulations using TCAD as well as measurement data for model validation.

2.2 Different approaches for HEMT modeling

In contrast to Silicon FETs, the operation of HEMTs is determined by the conductivity of the “2 Dimensional Electron Gas” (2DEG) located near the heterointerface. Though the channel in a Silicon MOSFET is similar in many

Fig. 2.1: Band Diagram of (a) wide and narrow bandgap semiconductors (b) Formation of 2DEG at the interface of wide and narrow bandgap semiconductors. ΔE_c and ΔE_v represent the conduction and valence band offset, while χ denotes the electron affinity [30].

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respects to that in a heterostructure, the values of certain parameters force us to consider them differently. In a modulation doped AlGaAs/GaAs HEMT, the small electron effective mass in GaAs gives rise not only to strong degeneracy effects under a moderate level of the sheet concentration of the channel electrons but also to a strong effect of the transversal quantization of channel electrons, as shown in Fig. 2.1. In a Si-MOSFET channel, both of these factors are less pronounced. So, it is rational to have a different approach for HEMT modeling compared to Si-FETs by incorporating coupled Poisson-Schrödinger (PS) solution.

The first approach is to have a self-consistent solution of PS equation by using the finite-difference method (FDM). Real space is divided into discrete mesh points and the wave function is solved within those discrete spacing. The one-dimensional, one-electron Schrodinger equation is given by [1]

$$-\frac{\hbar^2}{2} \frac{d}{dx} \left(\frac{1}{m^*(x)} \frac{d}{dx} \right) \psi(x) + V(x) \psi(x) = E \psi(x) \quad (2.1)$$

where $\psi(x)$ is the electron wave function, E is the total energy, V is the potential energy, $\hbar$ is reduced Planck's constant, and m^* is the effective mass. Applying the Poisson's equation at the hetero-interface, one can write

$$\frac{d}{dx} \left(\epsilon_{\text{uid}}(x) \frac{d}{dx} \right) \phi(x) = -\frac{q [N_D(x) - n(x)]}{\epsilon} \quad (2.2)$$

where ϵ_{uid} is the dielectric constant, ϕ is the electrostatic potential, $N_D(x)$ is the ionized donor concentration, and $n(x)$ is the electron density distribution. In a

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quantum well of arbitrary potential energy profile, the potential energy V is related to the electrostatic potential ϕ as follows:

$$V(x) = -q\phi(x) + \Delta E_c(x) \quad (2.3)$$

where ΔE_c is the conduction band offset at the hetero-interface. The wave function $\psi(y)$ in (2.1) and electron density $n(x)$ in (2.2) are related by

$$n(x) = \sum_{k=1}^n \psi_k^*(x) \psi_k(x) n_k \quad (2.4)$$

where n is the number of bound states, and n_k is the electron occupation for each state. Based on the Fermi-Dirac statistics, the electron concentration for each state can be expressed by:

$$n_s = \frac{m^*}{\pi \hbar^2} \int_{E_k}^{\infty} \frac{dE}{1 + e^{(E-E_f)/kT}} = \frac{m^* kT}{\pi \hbar^2} \ln \left[1 + e^{\frac{E_f - E_k}{kT}} \right] \quad (2.5)$$

where E_k is the Eigen energy. Now, iterative solution of (2.1)-(2.5) will give the 2DEG concentration profile as well as the potential in a heterostructure. This approach is implemented in mostly available P-S solver as in TCAD. However, this procedure is time consuming and hence not applicable for circuit designers.

A simpler way to solve this problem is by the assumption of a triangular quantum well at the hetero-interface. The potential well in which the 2DEG is trapped is triangular close to the heterojunction, although it flattens out in the buffer. Assuming that the well is perfectly triangular, one can use the relation

$$V(x) = qFx \quad (2.6)$$

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where q is the electronic charge and F is the electric field. After solving (2.1) using (2.6), one can express the quantized energy levels as

$$E_n = c_n \left[\frac{(qF\hbar)^2}{2m} \right]^{1/3} = c_n \left[\frac{\hbar^2}{2m} \left(\frac{q^2 n_s}{\epsilon_{\text{uid}}} \right)^2 \right]^{1/3}, \quad n = 0, 1, 2, 3, \dots \quad (2.7)$$

$$= \gamma_n n_s^{2/3}, \quad n = 0, 1, 2, 3, \dots$$

where c_n can be obtained from the so called Airy function and is equal to 2.338 for the lowest energy level. From WKB theory, c_n can be approximately expressed as

$$c_n \approx \left[\frac{3}{2} \pi \left(n - \frac{1}{4} \right) \right]^{2/3} \quad (2.8)$$

Yoshida [1] made a comparison between the self-consistent 2D exact model, 3-D Fermi model and the quantum mechanical model with triangular well approximation. The classical approach using Fermi statistics was found reasonably accurate although computationally difficult due to the Fermi integral. The triangular well model may need some tuning to exactly match the self-consistent solution by replacing F in (2.7) with jF , where j is the tuning parameter ranging between 0 and 1 as shown in Fig. 2.2 (a). A comparison of the simulated 2DEG capacitance from AlGaIn/GaN diode using different statistics is shown in Fig. 2.2 (b). It is seen that classical Boltzmann statistics always over-estimates the capacitance in moderate- as well as strong-inversion region. The Fermi statistics shows a closer match with the coupled P-S solution in the strong inversion but still overestimates the capacitance value in the moderate-inversion. This mismatch in the moderate-inversion regions is one of the major emphases of this work which will be presented in the later sections.

Fig. 2.2: Comparison of 2 DEG electron concentration variation with gate voltage for various physical models [1]

For compact modeling of HEMT devices, instead of relying on the coupled P-S solution, most literatures follow the work of Delagebeaudeuf and Linh [2] whereby only 2 subbands are considered, and the 2DEG density n_s is given by

$$n_s = Dv_{\text{th}} \ln \left[\left(1 + e^{(E_f - E_0)/v_{\text{th}}} \right) \left(1 + e^{(E_f - E_1)/v_{\text{th}}} \right) \right] \quad (2.9)$$

$$E_0 = \gamma_0 n_s^{2/3} \quad (2.9a)$$

$$E_1 = \gamma_1 n_s^{2/3} \quad (2.9b)$$

where D is the density of states of the 2-DEG associated with a single quantized energy level, with E_0 and E_1 being the two lowest subbands in the triangular well with respect to the conduction-band edge at the heterointerface, γ_0 and γ_1 are the constants derived from (2.7) related to lowest and second subband and

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$v_{th} = kT/q$ is the thermal voltage. The energy-band diagram of a generic AlGaIn/GaN metal-insulator-semiconductor (MIS)-HEMT is shown in Fig. 2.3, in which physical parameters are shown by the respective labels. Φ_{MB} and Φ_{SB} represent the metal-to-insulator and insulator-to-GaN cap barrier height, respectively. T_{cap} , T_{ox} , d and e represent the thickness of insulator, GaN cap, AlGaIn barrier and AlGaIn undoped spacer layer, respectively. The generic MIS-HEMT includes a cap layer with the same material as the unintentionally-doped (UID) body, which automatically becomes a HEMT if T_{cap} , T_{ox} , Φ_{MB} , and Φ_{SB} are set to zero.

By applying Gauss Law at the 2DEG interface [2], n_s in (2.9) can be related to the gate (V_g) and channel (V_c) voltages as

$$n_s = \frac{C_d}{q} (V_g - V_{off} - \phi_s) = \frac{C_d}{q} (V_g - V_{off} - V_c - E_f) \quad (2.10)$$

where the Fermi potential, E_f in eV, is referenced to the bottom of the triangular well (conduction-band edge at $x = 0$), and the surface potential, ϕ_s in V, is referenced to the Fermi level in the body where the channel voltage $V_c = V_s$ or V_d at the source or drain ends ($y = 0$ or gate length L_g), respectively, given by

$$\phi_s(V_c) = V_c + E_f(V_c) \quad (2.11)$$

where C_d is an effective capacitance (per unit area) between the gate and 2DEG, and V_{off} is the cutoff voltage below which it is in “subthreshold” conduction. By assuming the AlGaIn barrier layer being fully depleted and ignoring the electron charge in the cap layer, C_d and V_{off} can be expressed as

Fig. 2.3: Band Diagram of (a) MIS-HEMT structure obtained from coupled Poisson-Schrodinger solution (b) Zoom-in view of the triangular quantum well with two sub-bands. Fermi potential (in volts) is referenced to the conduction-band edge at the heterointerface ($x = 0$). Electrostatic potential and voltage (in volts) are referenced to the Fermi level in the body.

$$C_d = \frac{\varepsilon_b}{d \left(1 + \frac{\varepsilon_b T_{\text{ox}}}{\varepsilon_{\text{ox}} d} + \frac{\varepsilon_b T_{\text{cap}}}{\varepsilon_{\text{cap}} d} \right)} \quad (2.12)$$

$$V_{\text{off}} = \Phi_{\text{MB}} - \Phi_{\text{SB}} - \left(\frac{T_{\text{ox}}}{\varepsilon_{\text{ox}}} + \frac{T_{\text{cap}}}{\varepsilon_{\text{cap}}} \right) q N_b (d - e) - \frac{q N_b (d - e)^2}{2 \varepsilon_b} - \frac{q \sigma d}{\varepsilon_b} \quad (2.13)$$

where N_b is the doping concentration of the AlGaN barrier layer, ε_b and ε_{ox} are the permittivities of the barrier layer and insulator, respectively, and σ is the polarization-induced charge density at the heterointerface [36], [37].

It is evident that n_s in (2.9) is a complicated transcendental function of V_g and hence is not suitable for compact models. However, exact numerical solutions of (2.9) and (2.10) can be easily obtained with n_s as an input parameter in which E_f as well as E_0 and E_1 can be obtained from (2.9), and then, V_g from (2.10). The derived analytic relation for $E_f(n_s)$ versus $V_g(n_s)$ is given by

$$E_f(n_s) = v_{\text{th}} \ln \left\{ \frac{-B_f + \sqrt{B_f^2 - 4A_f C_f}}{2A_f} \right\} \quad (2.14)$$

$$A_f = a_0 a_1; \quad B_f = a_0 + a_1; \quad C_f = 1 - e^{n_s / D v_{\text{th}}} \quad (2.14a)$$

$$a_0 \equiv e^{-E_0 / v_{\text{th}}} = e^{-\gamma_0 n_s^{2/3} / v_{\text{th}}} \quad (2.14b)$$

$$a_1 \equiv e^{-E_1 / v_{\text{th}}} = e^{-\gamma_1 n_s^{2/3} / v_{\text{th}}} \quad (2.14c)$$

$$V_g(n_s) = \frac{qn_s}{C_d} + V_{\text{off}} + E_f(n_s) \quad (2.15)$$

Thus, with n_s as an input parameter, the exact solution of E_f versus V_g can be obtained, which will serve as a reference for model validation throughout this chapter. The variation of $E_f(V_g)$ with V_g in an AlGaIn/GaN HEMT is shown in Fig. 2.4 by solving (2.14)-(2.15). The goal of “compact” 2DEG modeling is to

Fig. 2.4: Exact solution of E_f and E_0 computed from (2.9) – (2.15) showing the variation with gate to source voltage.

derive an explicit $E_f(V_g)$ expression as close to the exact solution as possible, which is suitable for terminal current/charge model formulations.

There are few compact models on HEMTs currently available in literature. Rashmi et al. [38] reported a charge control model based on piecewise solutions in the respective regions while other models based on semi-empirical or numerical calculations are reported in [30]–[38]. These models do not focus on the moderate-inversion regions in details. Khandelwal et al. [45]–

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[48] developed a physics based analytical n_s - E_f model; however the model does not account for the GaN buffer doping and the parasitic channel effects. Therefore, explicit $n_s(V_g)$ or $E_f(V_g)$ expressions capturing the moderate-inversion as well as other secondary effects is very much necessary which has been the main focus of this chapter.

2.3 URM for generic HEMTs

The idea behind this work is to solve the regional surface potentials and then to obtain the unified solution using smoothing functions. The variation of $E_f(V_g)$ in an AlGaIn/GaN HEMT is shown in Fig. 2.4 as $E_{f,\text{exact}}$ whereby the gate voltage regime is divided into three regions viz. Strong Inversion ($E_f > E_0$), Moderate Inversion ($E_f < E_0$ and $V_g > V_{\text{off}}$) and subthreshold region of operation ($V_g < V_{\text{off}}$).

2.3.1 Piecewise explicit regional surface potential solution

(a) Strong-inversion region ($E_f > E_0$)

For simplicity, similar to bulk-MOS in which $V_g \equiv V_{\text{gb}} - V_{\text{FB}}$ is defined as the flatband-shifted gate-to-bulk voltage, we define

$$V_{\text{go}} \equiv V_g - V_{\text{off}} - V_c = V_{\text{gc}} - V_{\text{off}} \quad (2.16)$$

In the strong-inversion (active) region, if $E_0 < E_f < E_1$, from (2.9) using the series approximation $\ln(1 + e^x) \approx x$, n_s can be expressed as

$$n_{s,0} \approx Dv_{\text{th}} \ln\left(1 + e^{(E_f - E_0)/v_{\text{th}}}\right) \approx D\left(E_f - \gamma_0 n_{s,0}^{2/3}\right) \quad (2.17a)$$

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Likewise, if $E_f > E_1$, n_s can be approximated as

$$\begin{aligned} n_{s,1} &\approx D(E_f - E_0) + D(E_f - E_1) \\ &= 2DE_f - D(\gamma_0 + \gamma_1)n_{s,1}^{2/3}. \end{aligned} \quad (2.17b)$$

In (2.17a) and (2.17b), the subscripts ‘0’ and ‘1’ denote n_s due to subband E_0 only and subbands E_1 , E_0 , respectively. Equations (2.17a) and (2.17b) are still implicit relations and are not suitable for compact models. E_f is small compared to V_{go} in the active region. So, from (2.10), the $(n_s)^{2/3}$ term can be approximated by taking a Taylor expansion to the first order as

$$n_s^{2/3} = \left[\frac{C_d}{q} (V_{go} - E_f) \right]^{2/3} \approx \left(\frac{C_d}{q} V_{go} \right)^{2/3} \left(1 - \frac{2}{3} \frac{E_f}{V_{go}} \right) \quad (2.18)$$

Substituting (2.18) into (2.17a) and (2.17b), we obtain

$$n_{s,0} \approx DE_f - D\gamma_0 \left(\frac{C_d}{q} V_{go} \right)^{2/3} \left(1 - \frac{2}{3} \frac{E_f}{V_{go}} \right) \quad (2.19a)$$

$$n_{s,1} \approx 2DE_f - D(\gamma_0 + \gamma_1) \left(\frac{C_d}{q} V_{go} \right)^{2/3} \left(1 - \frac{2}{3} \frac{E_f}{V_{go}} \right) \quad (2.19b)$$

Combining (2.10) with (2.19a) and (2.19b), explicit regional E_f solutions can be expressed as

$$E_f = \begin{cases} E_{f,0} = \mathcal{M}_0 \cdot V_{go} & (E_0 < E_f < E_1) \\ E_{f,1} = \mathcal{M}_1 \cdot V_{go} & (E_f > E_1) \end{cases} \quad (2.20)$$

where

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$$\mathcal{M}_0(V_{\text{go}}) = \frac{\tilde{C}_d V_{\text{go}}^{1/3} + \gamma_0 \left(\tilde{C}_d D \right)^{2/3}}{\left(1 + \tilde{C}_d \right) V_{\text{go}}^{1/3} + \frac{2\gamma_0}{3} \left(\tilde{C}_d D \right)^{2/3}} \quad (2.20a)$$

$$\mathcal{M}_1(V_{\text{go}}) = \frac{\frac{\tilde{C}_d}{2} V_{\text{go}}^{1/3} + \frac{\gamma_0 + \gamma_1}{2} \left(\tilde{C}_d D \right)^{2/3}}{\left(1 + \frac{\tilde{C}_d}{2} \right) V_{\text{go}}^{1/3} + \frac{\gamma_0 + \gamma_1}{3} \left(\tilde{C}_d D \right)^{2/3}} \quad (2.20b)$$

and

$$\tilde{C}_d \equiv \frac{C_d}{qD} \quad (2.20c)$$

is a (dimensionless) effective capacitance, given by (2.20c), normalized to qD .

After obtaining the two active regional solution with $E_f > E_I$ and $E_f < E_I$, a unified E_f model for the strong-inversion region can be constructed by the following smoothing function

$$E_{f,\text{str}} = \mathcal{M} \cdot V_{\text{go}} \quad (2.21)$$

$$\begin{aligned} \mathcal{M} &= \mathcal{G}(\mathcal{M}_1, \mathcal{M}_0; \alpha) \\ &= 0.5 \left(\mathcal{M}_1 + \mathcal{M}_0 + \alpha - \sqrt{(\mathcal{M}_1 - \mathcal{M}_0 - \alpha)^2 + 4\alpha\mathcal{M}_1} \right) \end{aligned} \quad (2.21a)$$

where α is a smoothing parameter. It can be seen that $\mathcal{M}$ in (2.21a) is the smaller one between $\mathcal{M}_0$ and $\mathcal{M}_1$. So, from (2.20) and (2.21), $E_{f,\text{str}}$ is taking the smaller value of $E_{f,0}$ and $E_{f,1}$, i.e., the regional solution with $\min\{|E_f - E_0|, |E_f - E_1|\}$.

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To avoid negative values in the square-root function for the unified solutions, the following smoothing function is used for (2.21):

$$\mathcal{M}_{\text{eff}} = \mathcal{M}|_{V_{\text{go}}=V_{\text{go,act}}} \quad (2.22)$$

$$V_{\text{go,act}} = 0.5 \left(V_{\text{go}} + \sqrt{V_{\text{go}}^2 + 4\varepsilon} \right) \quad (2.22a)$$

where ε is a smoothing parameter.

(b) Moderate-inversion region ($E_f < E_0$ and $V_{\text{go}} > 0$)

We define the moderate-inversion region as when E_f is lesser than E_0 as shown in Fig. 2.4. Applying the series approximation $\ln(1 + e^x) \approx e^x$, (2.9) can be simplified to

$$n_s \approx Dv_{\text{th}} e^{(E_f - \gamma_0 n_s^{2/3})/v_{\text{th}}} \quad (2.23)$$

It is important to note that in the moderate-inversion region, E_f is still less than V_{go} , except for V_{g} being a few millivolts around V_{off} . Hence, (2.18) can still be used to simplify (2.23). Substituting (2.18) into (2.23), and together with (2.10), (2.23) can be expressed as

$$\frac{C_g}{q} (V_{\text{go}} - E_f) = Dv_{\text{th}} \left(e^{-3\lambda_0 V_{\text{go}}/2v_{\text{th}}} \cdot e^{(1+\lambda_0)E_f/v_{\text{th}}} \right) \quad (2.24)$$

where

$$\lambda_0 = \frac{2\gamma_0}{3V_{\text{go,act}}} \left(\frac{C_d}{q} V_{\text{go,act}} \right)^{2/3} \quad (2.24a)$$

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in which $V_{go,act}$ is used for V_{go} for smoothing considerations. By inspection, it is found that (2.24) has a solution for E_f in the form of a *Lambert W* function, $L\{w\}$, if λ_0 is treated as a parameter:

$$E_{f,mod} = V_{go} - \frac{v_{th}}{1 + \lambda_0} \mathcal{L} \left\{ \theta e^{(1+\lambda_0)V_{go}/v_{th}} \right\} \quad (2.25)$$

where

$$\theta = \frac{1 + \lambda_0}{\tilde{C}_d} e^{-3\lambda_0 V_{go}/2v_{th}} \quad (2.25a)$$

$E_{f,mod}$ in (2.25) can thus be taken as the regional solution in moderate-inversion region.

(c) Subthreshold region ($V_{go} < 0$)

In the subthreshold (off) region, n_s is very small, $E_f - E_0$ and $E_f - E_1$ are negative.

So, the implicit n_s relation in (2.9) can be approximated as

$$n_s \approx Dv_{th} \left(e^{\left(E_f - \gamma_0 n_s^{2/3} \right) / v_{th}} + e^{\left(E_f - \gamma_1 n_s^{2/3} \right) / v_{th}} \right) \approx 2Dv_{th} e^{E_f / v_{th}} \quad (2.26)$$

Combining (2.10) with (2.26), the subthreshold regional E_f solution is found to be a *Lambert W* function and can be expressed as

$$\begin{aligned} E_{f,sub} &= V_{go} - v_{th} \mathcal{L} \left\{ \frac{2qD}{C_d} e^{V_{go}/v_{th}} \right\} \\ &\approx V_{go} - \frac{2v_{th}}{\tilde{C}_d} e^{V_{go}/v_{th}} \end{aligned} \quad (2.27)$$

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where the second approximation, only valid when $V_{go} < 0$, is crucial in obtaining the unified E_f solution. The exponential term in (2.27) is very small compared to V_{go} and is, in fact, negligible. However, it is a crucial term that ensures the correct functionality of n_s and E_f in the subthreshold region.

2.3.2 Unified regional surface potential solution

(a) Moderate to strong-inversion (“active”) region

From Fig. 2.4, it is observed that $E_f = E_0$ marks the boundary between moderate and strong-inversion regions. The corresponding gate voltage, $V_{g,CR}$, is defined as a “critical voltage” (similar to “threshold”), which can be solved from (2.9) and (2.10) by putting $E_f = E_0$ as

$$V_{g,CR} = V_{off} + \frac{v_{th}}{\tilde{C}_d} \ln(2) + \gamma \left[D v_{th} \ln(2) \right]^{2/3} \quad (2.28)$$

$$V_{go,CR} \equiv V_{g,CR} - V_{off} \cdot \quad (2.28a)$$

To obtain a unified E_f expression that is valid from moderate to strong-inversion regions, namely, the “active region,” the following interpolation function is used:

$$E_{f,act} = \frac{2\mathcal{M}_{eff} V_{go,CR} \ln \left(1 + \exp \left(\frac{V_{go,act}}{2V_{go,CR}} \right) \right)}{1 + \eta \frac{\mathcal{M}_{eff} V_{go,CR}}{E_{f,mod}} \exp \left(-\frac{V_{go,act}}{2V_{go,CR}} \right)} \quad (2.29)$$

where η is a fitting parameter that ensures a smooth transition from moderate to strong-inversion regions. (2.29) gives the asymptotic strong-inversion solution

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(2.21) when $V_{go} \gg V_{go,CR}$. However, to develop a scalable model, it is desirable to derive a physical expression for η which should be valid for any device dimensions.

In the moderate-inversion region, (2.29) can be approximately expressed as

$$E_{f,act} \approx E_{f,mod} \frac{2\ln\left(1 + e^{V_{go,act}/2V_{go,CR}}\right)}{\eta e^{-V_{go,act}/2V_{go,CR}}} \quad (2.30)$$

which gives an ideal estimate of η if we set $E_{f,act} = E_{f,mod}$:

$$\eta_{est} = \frac{2\ln\left(1 + e^{V_{go,act}/2V_{go,CR}}\right)}{e^{-V_{go,act}/2V_{go,CR}}} \quad (2.31)$$

However, (2.31) cannot be used as it will affect the strong-inversion characteristics. By plotting $E_{f,act}$ in (2.30) with $\eta = 1$, together with $E_{f,mod}$ in (2.25), as shown in Fig. 2.5, we note that the two curves intersect at $E_f = 0$. From (2.30) and (2.31), the corresponding gate voltage at this intersection point ($E_{f,act} = E_{f,mod}$) is defined as $V_{g,SUB}$ (“subthreshold”), which can be used as an estimate of η in (2.30), assuming η_{est} is linear around $V_{g,SUB}$:

$$\eta = \eta_{est} \Big|_{V_{go,act}=V_{go,SUB}} \quad (2.32)$$

$$V_{go,SUB} \equiv V_{g,SUB} - V_{off} \quad (2.32a)$$

Nevertheless, we still need to find an explicit expression for $V_{go,SUB}$. For $E_f = 0$, from (2.9) and (2.10), one can write

$$\frac{C_d}{q}(V_{go}) = Dv_{th} \exp \left[-\frac{\gamma_0}{v_{th}} \left(\frac{C_d}{q} V_{go} \right)^{2/3} \right] \quad (2.33)$$

in which the (exact) solution of V_{go} is $V_{go,SUB}$. It was observed that $V_{g,SUB}$ is always close to V_{off} for a wide range of device parameters; hence, $(V_{go})^{2/3}$ can be approximated by a linear expression:

$$(V_{go})^{2/3} \approx aV_{go} + b \quad (2.34)$$

with $a = 1.14 \text{ V}^{-1/3}$ and $b = 0.09 \text{ V}^{2/3}$ being fixed values, independent of device

Fig. 2.5: Regional E_f solution in moderate-inversion [solid line, (2.29)] and approximate moderate/strong-inversion (active) regional E_f solution with $\eta = 1$ [dashed line, (2.30)] versus V_{gs} , compared with the exact E_f solution [circle, (2.14) and (2.15)], in which the intersection point defines the subthreshold voltage, $V_{g,SUB}$, with $E_f = 0$. Inset: the Newton-Raphson iterative solution of $V_{go}^{2/3}$ from (2.33) versus V_{go} and its linear approximation from (2.34) on the left y-axis, and the error (difference) on the right y-axis.

TABLE II
EXACT & APPROXIMATE SOLUTION OF $V_{g,SUB}$ ($V_{off}=-3$)

d (nm)	Exact Solution from (2.33) (V)	Approximate Solution from (2.35) (V)
16	-2.879	-2.8774
20	-2.8491	-2.8456
24	-2.8189	-2.8148
30	-2.77	-2.7705

parameters. The left- and right-hand sides of (2.34) are plotted in Fig. 2.5 (inset), in which the linear approximation has an error less than $0.1 \text{ V}^{2/3}$. Now, replacing the $(V_{go})^{2/3}$ term in (2.33) by (2.34), the solution of (2.33) is a *Lambert W* function, given by

$$V_{go,SUB} = \left(-\frac{1}{a\omega_s} \right) \mathcal{L} \left\{ -\frac{a\omega_s v_{th}}{\tilde{C}_d} e^{b\omega_s} \right\} \quad (2.35)$$

$$\omega_s \equiv -\frac{\gamma_0}{v_{th}} \left(\frac{C_d}{q} \right)^{2/3}. \quad (2.35a)$$

The differences in $V_{g,SUB}$ between the explicit (approximate) solution (2.35) and the implicit (exact) solution from (2.33) are found to be around 0.5–4 mV for barrier thicknesses (d) ranging from 16 to 30 nm as shown in table II. The active region unified solution $E_{f,act}$ from (2.29) is then validated with the exact solution for different barrier thickness d as shown in Fig. 2.6, where a nice match is obtained from moderate to strong- inversion.

Fig. 2.6: Variation of the E_f solution (2.29) with V_{gs} valid from moderate to strong inversion ($E_{f,act}$) for different dimensions of the AlGaN barrier layer for a fixed $V_{off}=-3V$.

(b) Unified single-piece solution

A single-piece explicit E_f expression that is valid in all regions can be obtained by joining $E_{f,act}$ in (2.29) and $E_{f,sub}$ in (2.27) by one unified equation through the use of an interpolate function as

$$E_f(V_c) = V_{go} - \Delta E_f \quad (2.36)$$

$$\Delta E_f = \frac{2v_{th} \left(1 - E_{f,act} / V_{go}\right) \ln \left(1 + \exp \left(V_{go} / 2v_{th}\right)\right)}{1 + \tilde{C}_d \left(1 - E_{f,act} / V_{go}\right) \exp \left(-V_{go} / 2v_{th}\right)} \quad (2.37)$$

It can be seen that (2.37) approaches $V_{go} - E_{f,act}$ when $V_{go} \gg 2v_{th}$, in which (2.36) follows (2.29) in moderate/strong-inversion (active) region; and (2.29) approaches $\mathcal{M}_{eff} V_{go,act}$ or $\mathcal{M} V_{go}$ when $V_{go} \gg V_{go,CR}$ in the strong-inversion region. Equation (2.37) approaches $\left(2v_{th} / \tilde{C}_d\right) e^{V_{go}/v_{th}}$ when $V_{go} \ll 2v_{th}$ in

the subthreshold region.

The importance of the moderate-inversion region modeling can be understood by computing a single-piece explicit E_f model without considering moderate inversion regional piece as given by

$$\Delta E_f = \frac{2v_{th}(1 - \mathcal{M}_{eff}) \ln(1 + e^{V_{go}/2v_{th}})}{1 + \tilde{C}_d(1 - \mathcal{M}_{eff})e^{-V_{go}/2v_{th}}} \quad (2.38)$$

In (2.38), E_f approaches $E_{f, \text{str}}$ when $V_g > V_{\text{off}}$ and follows the $E_{f, \text{sub}}$ in the sub- V_{off} region. The various regional and unified E_f solutions as an explicit function of V_g are plotted in Fig. 2.7(a) and compared with the exact E_f solution. The exact E_0 solution is also shown, whose intersection with E_f defines the critical voltage, $V_{g, \text{CR}}$, the boundary between moderate- and strong-inversion regions. The subthreshold voltage, $V_{g, \text{SUB}}$, as defined by the condition $E_f = 0$, is also shown, which is close to V_{off} , the boundary between moderate inversion and subthreshold regions. The extracted values of $V_{g, \text{CR}}$, $V_{g, \text{SUB}}$, and V_{off} are all close to those from their analytical expressions given in (2.28), (2.35), and (2.13), respectively, which makes the CM scalable with device parameters. It is evident that while the regional solution $E_{f, \text{str}}$ follows the exact solution in strong-inversion region, the other regional solution $E_{f, \text{mod}}$ fits well in the moderate-inversion region. The unified solutions of these regional pieces $E_{f, \text{act}}$ thus match well with the exact solution throughout moderate- and strong-inversion region. However, by closer inspection, $E_{f, \text{act}}$ does not capture the correct slope in the subthreshold region. The corresponding derivatives of E_f w.r.t. V_{gs} are plotted in Fig. 2.7(b), showing the model smoothness.

Fig. 2.7: (a) Regional E_f solutions versus V_{gs} : $E_{f, \text{str}}$ [dashed line, (2.21)], $E_{f, \text{mod}}$ [solid line, (2.25)], $E_{f, \text{sub}}$ [dash-dotted line, (2.27)], $E_{f, \text{act}}$ [dotted line, (2.29)], and single piece unified E_f [crosses, (2.36) and (2.37)], compared with the exact E_f [dots, (2.14) and (2.15)]. The exact E_0 is also plotted [long-dashed line, (2.9)] (b) Corresponding derivatives of the regional E_f solutions w.r.t. V_{gs} . Inset: the differences of the regional E_f solutions w.r.t. the unified E_f [(2.36) and (2.37)]. The overall error of the unified E_f is the minimum of errors in $E_{f, \text{act}}$ and $E_{f, \text{sub}}$, shown by the circle.

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The differences in the regional models w.r.t. the unified solution are shown in the inset of Fig. 2.7(b). The large difference between $E_{f,\text{mod}}$ (2.25) and $E_{f,\text{sub}}$ (2.27) in the subthreshold region, although not visually observable in their values from Fig. 2.7(a), shows the importance of the second approximation in (2.27) for the correct subthreshold slope with an exponential function instead of the Lambert W function. The improved accuracy in the moderate-inversion modeling is evident by comparing the unified E_f model (2.36) with ΔE_f using (2.37) and (2.38), as shown in the inset of Fig. 2.7(b). By considering the moderate inversion regional piece, the overall error between the model and the exact solution reduces which signifies the importance of the moderate inversion regional solution. Previous HEMT CM [49] based on (2.38) did not consider the moderate inversion region, instead connected the strong inversion with subthreshold regional piece and thus resulted in increased error when compared with exact solution. The importance of moderate inversion regional solution will be further discussed in capacitance modeling in the next section.

(c) Surface Potential Solution Validation

The developed complete E_f - V_g solution is validated with exact solution for different AlGaIn barrier thickness. Fig. 2.8 shows the unified E_f model versus V_g , compared with the exact solutions, and model scaling with the barrier thickness d of 10, 15, and 20 nm. The differences (or absolute errors) between the unified model and the exact solution are plotted in Fig. 2.9 (a) showing an overall error below ~ 5 mV. The corresponding derivatives of E_f w.r.t. V_{gs} are shown in Fig. 2.9 (b), demonstrating the model smoothness. The developed model is found to be scalable over all major device parameters with errors in

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the millivolt range, due to the analytical models $V_{g,CR}$ (2.28), $V_{go,SUB}$ (2.35), as well as V_{off} (2.13) with physical parameters [3].

Fig. 2.8: Unified E_f solutions [(2.36) and (2.37)] versus V_{gs} , compared with the exact solutions for different barrier thicknesses (d).

Fig. 2.9: First order derivatives of E_f w.r.t V_{gs} Inset: Absolute error (difference) between the unified E_f model and the exact E_f solution.

2.3.3 Gate capacitance model formulation & validation

With an accurate n_s - E_f solution, the 2DEG capacitance, which is proportional to the derivative of E_f with respect to V_g , can be modeled correctly. We referred to the 2DEG density n_s given by (2.10), from which the AlGaIn/GaN diode capacitance C_{gg} can be expressed as

$$C_{gg} = q \frac{dn_s}{dV_g} = C_d \left(1 - \frac{dE_f}{dV_g} \right) \quad (2.39)$$

Again n_s related to E_f and E_0 is given by (2.9), from which dn_s/dV_g can be written as

$$\frac{dn_s}{dV_g} = \frac{D}{qe^{n_s/Dv_{th}}} \left(e^{n_s/Dv_{th}} - 1 \right) \left(\frac{dE_f}{dV_g} - \frac{dE_0}{dV_g} \right) \quad (2.40)$$

From (2.9a), dE_0/dV_g can be written as

$$\frac{dE_0}{dV_g} = \frac{2}{3} \gamma_0 n_s^{-1/3} \frac{dn_s}{dV_g} \quad (2.41)$$

Combining (2.39)-(2.41), the gate capacitance C_{gg} can be expressed as,

$$C_{gg} = \frac{C_{K1}}{1 + C_{K1}C_{K2}} \quad (2.42)$$

$$C_{K1} = \frac{D(e^{n_s/Dv_{th}} - 1)}{e^{n_s/Dv_{th}}} \quad (2.42a)$$

$$C_{K2} = \frac{1}{C_g} + \frac{2\gamma_0}{3} n_s^{-1/3} \quad (2.42b)$$

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The previous section presents the explicit solution of n_s from (2.10), the gate capacitance can be directly obtained from (2.42) once n_s is obtained. To validate the 2DEG capacitance model, it is compared with the measured MIS-diode C–V data using the physical parameters ($T_{\text{ox}} = 8.8$ nm and $T_{\text{cap}} = 2$ nm) as shown in Fig. 2.10 (a) and a good match is observed. For comparison with the simpler model (2.38) without moderate inversion, model playback is done without changing any physical parameters (dashed line), which showed larger discrepancies. If V_{off} is tuned to match the near- V_{off} transition behavior, a large discrepancy will occur in the moderate-inversion region. This result justifies the importance of moderate-inversion in the unified E_f solution. Also the comparison of model with coupled P-S solution from TCAD for different barrier thickness d of 15, 18, and 22 nm is shown in Fig. 2.10 (b) and a good scalability has been observed.

(a)

(b)

Fig. 2.10: (a) Measured diode C_{gg} - V_{gs} characteristics (symbol) with a 8.8-nm HfO₂ and a 2-nm cap layer MIS-HEMT, compared with the model.

With moderate-inversion solution, the model match nicely with measurement data in the near- V_{off} region (b) Model validation with coupled P-S solution for different AlGaIn barrier thickness (d)

2.4 Unified regional drain current model of HEMTs

Most of the existing compact models are developed based on the charge-sheet approximation. It is assumed that the depletion region under the gate is free of mobile carriers so that the depletion approximation is valid. From current continuity, $I_{ds} = -\mu W Q_i(y) dV/dy$, the drain current can be found by integrating the inversion charge density from source $y=0$ to drain $y=L_{eff}$

$$\int_0^{L_{eff}} I_{ds} dy = -\mu W \int_0^{V_{ds}} Q_i dV \quad (2.43)$$

where L_{eff} is the effective channel length, μ is the effective mobility, W is the width of the HEMT and $Q_i(y)$ denotes the inversion charge. If one performs a change of variable of the surface potential and quasi-Fermi potential while assuming charge-sheet approximation, (2.43) becomes [50]

$$\int_0^{L_{eff}} I_{ds} dy = -\mu W \int_0^{V_{ds}} (Q_i(y) d\phi(y) - v_{th} dQ_i(y)) \quad (2.44)$$

The integrated drain current is then given as [50]

$$I_{ds} = \beta \left\{ (V_g - V_{off}) (\phi_{s,d} - \phi_{s,s}) - \frac{1}{2} (\phi_{s,d}^2 - \phi_{s,s}^2) + v_{th} (\phi_{s,d} - \phi_{s,s}) \right\} \quad (2.45)$$

where $\beta = W\mu C_{ox}/L_{eff}$ is the gain factor, $\phi_{s,d}$ and $\phi_{s,s}$ are the surface potential at drain and source end, respectively. The first term in (2.45) is usually referred to as the drift-component corresponding to the results of integration for the first term in (2.44) while the second term is the diffusion-component corresponding to second term in (2.44). This drain current model is accurate, but it also results in a complicated charge model [51] had there been enough bulk charge.

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Nevertheless, this will cause a violation of the Gummel symmetry test (GST).

However, for HEMT devices with undoped buffer, (2.45) reduces to

$$I_{ds} = \beta(q_i + v_{th})\Delta\phi_s \quad (2.46)$$

where

$$q_i = (V_g - V_{off} - \overline{\phi_s}) \quad (2.47)$$

$$\Delta\phi_s = \phi_{s,d} - \phi_{s,s} \quad (2.48)$$

and

$$\overline{\phi_s} = \frac{\phi_{s,d} + \phi_{s,s}}{2} \quad (2.49)$$

is the average surface potential. In the URM approach, the drain-current model (2.46) is further approximated with a “pinned surface potential” concept, where it can be rewritten as [50]

$$I_{ds} = \beta(q_i + v_{th})V_{ds} \quad (2.50)$$

with

$$\Delta\phi_s \approx V_{ds} = V_{ds,eff} \quad (2.51)$$

in which V_{ds} is to be replaced by the effective drain-source voltage, $V_{ds,eff}$ in current evaluation for correct linear (and strong inversion) to saturation (and subthreshold) behaviour. This form of drain current equation does not require accurate surface potential solution, as long as it has the correct subthreshold slope in $V_{ds,eff}$.

2.4.1 Effective mobility and transverse field degradation

The transverse field-dependent mobility is usually expressed with the well-known Matthiessen's rule for three scattering mechanisms [52],

$$\begin{aligned}\mu_0 &= \left(\frac{1}{\mu_{co}} + \frac{1}{\mu_{ph}} + \frac{1}{\mu_{sr}} \right)^{-1} \\ &= \frac{\mu_1}{1 + \left(\frac{\mu_1}{\mu_2} \right) E_{\text{eff}}^{\frac{1}{3}} + \left(\frac{\mu_1}{\mu_3} \right) E_{\text{eff}}^v}\end{aligned}\quad (2.52)$$

in which semi-empirical model for phonon scattering (μ_{ph}), surface roughness scattering (μ_{sr}), and Coulombic scattering (μ_{co}) are related to the effective transverse field, E_{eff} [51] by

$$\mu_{ph} = \frac{\mu_2}{E_{\text{eff}}^{\frac{1}{3}}} \quad (2.53)$$

$$\mu_{sr} = \frac{\mu_3}{E_{\text{eff}}^v} \quad (2.54)$$

$$\mu_{co} = \mu_1 \quad (2.55)$$

respectively. μ_1 is assumed as a constant with respect to the effective transverse field, μ_2 and μ_3 are related to acceptor density and absolute temperature, and v is (by default) 2 for NMOS and 1 for PMOS. Nevertheless, μ_1 , μ_2 , μ_3 and v are usually treated as fitting parameters to match the measurement data. The effective transverse field is related to the inversion charge as [51]

$$\begin{aligned}E_{\text{eff}} &= \frac{\zeta_n C_d}{\epsilon_{\text{uid}}} \left(\overline{V_{\text{gt}}} + \frac{\zeta_b}{\zeta_n} \Upsilon \sqrt{\phi_{\text{seff}}} \right) \cong \frac{C_d \overline{V_{\text{gt}}}}{2\epsilon_{\text{uid}}} \\ &= \frac{C_d (V_g - V_{\text{off}} - \overline{\phi_s})}{2\epsilon_{\text{uid}}} = \frac{C_d \Delta E_f (V_{\text{c,eff}})}{2\epsilon_{\text{uid}}}\end{aligned}\quad (2.55)$$

$$\overline{\Delta E_f(V_{c,\text{eff}})} = \frac{\Delta E_f(V_{s,\text{eff}}) + \Delta E_f(V_{d,\text{eff}})}{2} \quad (2.56)$$

where C_d is the AlGaIn capacitance similar to C_{ox} in MOSFET devices, $V_{\text{gt},c}$ ($c=s/d$) is the inversion charge normalized to C_d at the source/drain end, ζ_n (default=0.5) and ζ_b (default=1) are fitting parameters, Υ is the GaN buffer doping dependent body factor and ϵ_{uid} is the GaN permittivity. Normally for UID GaN buffer, the second term involving Υ tend to zero, and thus is ignored in (2.55). However, the effect of GaN buffer doping will be discussed in details in section 2.7, where the second term will no longer be ignored.

2.4.2 Lateral field mobility degradation

The mobility degradation due to lateral field, $E_y = -d\phi_s/dy$ begins to have more significant role over transverse-field degradation when V_{ds} increases beyond the gradual-channel approximation. At low lateral field (i.e., low V_{ds}), the velocity of carriers in the channel is proportional to E_y and begins to saturate when lateral field is larger than the saturation field, E_{sat} . The two-region piecewise velocity-field relation is [51]

$$v_0 = \frac{\mu_0 E_y}{1 + E_y / E_{\text{sat}}} \quad \text{if } E_y < E_{\text{sat}} \quad (2.57)$$

and

$$v_0 = v_{\text{sat}} \quad \text{if } E_y > E_{\text{sat}} \quad (2.58)$$

with

$$E_{\text{sat}} = \frac{v_{\text{sat}}}{2\mu_0} \quad (2.59)$$

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for electrons, where v_{sat} is the saturated electron velocity. The effective mobility is given as

$$\mu_{\text{eff}} = \frac{\mu_0}{\sqrt{1 + \delta_L \left(\frac{\phi_{s,d} - \phi_{s,s}}{E_{\text{sat}} L_{\text{eff}}} \right)^2}} \quad (2.60)$$

where δ_L is a fitting parameter for lateral field degradation.

2.4.3 Saturation voltage

The saturation voltage is defined as the voltage at which the current reaches its saturated value. Conventional compact models consider source and drain terminals such that drain terminal voltage is always higher than source terminal voltage for NMOS. Following the work of by [51], the source and drain terminals are treated as node labels (designated by layout), in which V_{ds} can be negative and the source/drain terminals are not swapped in model evaluation in a circuit simulator. The effective source/drain (S/D) voltage can be then expressed by [51]

$$V_{\text{ds,eff}} = V_{d,\text{eff}} - V_{s,\text{eff}} \quad (2.61)$$

$$\begin{aligned} V_{c,\text{eff}} &= \mathcal{G}\{V_{c,\text{sat}}, V_c; \delta\} \quad (c = s, d) \\ &= 0.5 \left(V_{c,\text{sat}} + V_c + \delta_s - \sqrt{(V_{c,\text{sat}} - V_c - \delta_s)^2 + 4\delta_s V_{c,\text{sat}}} \right) \end{aligned} \quad (2.62)$$

$$V_{d,\text{sat}} = \frac{V_{\text{gt},s} L_{\text{eff}} E_{\text{sat},s}}{V_{\text{gt},s} + L_{\text{eff}} E_{\text{sat},s} + 4v_{\text{th}}} + V_s \quad (2.63)$$

$$V_{s,\text{sat}} = \frac{V_{\text{gt},d} L_{\text{eff}} E_{\text{sat},d}}{V_{\text{gt},d} + L_{\text{eff}} E_{\text{sat},d} + 4v_{\text{th}}} + V_d \quad (2.64)$$

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$$E_{\text{sat},c} = 2v_{\text{sat}}/\mu_{0,c} \quad (c = s, d) \quad (2.65)$$

where δ_s is the smoothing parameter for (2.62), $E_{\text{sat},c}$ (c=s/d) is the effective saturation electric field at the source/drain end and v_{sat} is the saturation velocity.

2.4.4 Channel length modulation

Channel-length modulation (CLM) and velocity overshoot (VO) have been modeled based on energy-balance formulation [53] through an “effective Early voltage,”. The final short channel current equation including CLM/VO effects is given as [53]

$$I_{\text{ds}} = \overline{g_{\text{vo}}} I_{\text{ds}} \quad (2.66)$$

$$\overline{g_{\text{vo}}} = (g_{\text{vo},s} + g_{\text{vo},d}) / 2 \quad (2.67)$$

$$g_{\text{vo},d} = 1 + \left(\frac{V_d - V_{d,\text{eff}}}{V_{\text{Aeff},d}} \right) \quad (2.68)$$

where V_{Aeff} is the effective Early Voltage expressed as

$$V_{\text{Aeff},d} = \frac{\left(L_{\text{eff}} E_{\text{sat}} \left[1 + h_d (V_d - V_{d,\text{eff}}) \right] \right) + \delta_L V_{d,\text{eff}}}{\delta_L h_d V_{d,\text{eff}}} \quad (2.69)$$

$$h_d = \frac{\frac{\xi_c}{l^2} \left[1 + \sqrt{1 + \left(\frac{V_d - V_{d,\text{eff}}}{l E_{\text{sat}}} \right)^2} \right]}{\sqrt{1 + \left(\frac{V_d - V_{d,\text{eff}}}{l E_{\text{sat}}} \right)^2} - \frac{\xi_c}{l^2} (V_d - V_{d,\text{eff}})} \quad (2.69a)$$

where l is characteristic length and ξ_c is a fitting parameter.

2.4.5 Drain Induced Barrier Lowering

The short-channel model is developed based on the quasi 2-D potential lowering ($\delta\phi_s$) [34] by applying the Gauss law to a fixed rectangular box of depth (X_{dm}) and effective channel length (L_{eff}), which is given by

$$\delta\phi_{s,c}(y) = (V_{bi,c} + V_c - \phi_s) \frac{\sinh[(L_{eff} - y)/\lambda_c]}{\sinh(L_{eff}/\lambda_c)} \quad (c = s, d) \quad (2.70)$$

$$\lambda_c = \sqrt{\frac{\epsilon_{uid}}{C_d} \frac{0.5(X_{dm,s} + X_{dm,d})}{\eta_{sc}}} \quad (2.70a)$$

where $V_{bi,s}$ and $V_{bi,d}$ are the source and drain built-in potentials, respectively, ϕ_s is the long-channel surface potential, $X_{dm,c}$ is the maximum depletion width at the source/drain end ($c=s/d$), η_{sc} is the prefactor for quasi-2D solution. As the channel length continues to decrease and when $V_{ds} \neq 0$, the minimum potential occurs at $y=y_{min}$, where y_{min} is given as [34]

$$y_{min} = \frac{L_{eff}}{2} - \frac{\gamma_{sc}\lambda_c}{2} \ln \frac{V_{bi} + V_d - 2\phi_F}{V_{bi} + V_s - 2\phi_F} \quad (2.71)$$

where γ_{sc} is a fitting parameter. The drain induced barrier lowering (DIBL) model is based on potential lowering calculated at $y=y_{min}$ and is given as [34]

$$\begin{aligned} \delta\phi_s &= \delta\phi_{s,s}(y_{min}) + \delta\phi_{s,d}(y_{min}) \\ &= \frac{(V_{bi,s} + V_{bi,d} - 2\phi_s)}{2 \cosh(y_{min}/\lambda)} + \frac{\alpha_{dibl}(V_s + V_d)}{2 \cosh(y_{min}/\lambda)} \end{aligned} \quad (2.72)$$

where α_{dibl} is a fitting parameters. Finally, $\delta\phi_s$ is included in the flatband voltage (V_{FB}) to obtain the accurate short-channel surface potential. The above model calculates $\delta\phi_s$ in an iterative way as it is again included in V_{FB} after the long channel surface potential calculation. The above iteration has been effectively

Fig. 2.11: Schematic of sub circuit approach for R_s/R_d model.

incorporated in Verilog-A simulator and the DIBL effects are captured effectively, as will be shown in the later section.

2.4.6 Source/ Drain access resistance

The source and drain access regions are normally long enough in HEMT devices for high breakdown voltage, so accurate modeling of series resistance is very important. In our model, the source and drain resistance are modeled using a sub-circuit approach in Verilog-A. The schematic is shown in Fig. 2.11, where the intermediate voltages are termed as V_{si} and V_{di} at the source and drain side respectively. Due to the high field effects, the series resistance R_s and R_d is not a linear function but depends on the velocity saturation effects as [54]

$$R_s = \frac{L_{gs}}{qW\mu_{rs}\sigma} \left(1 + \zeta_{rs} \left(\frac{\mu_{rs}(V_{si} - V_s)}{v_{sats}L_{gs}} \right)^2 \right)^{\frac{1}{2}} \quad (2.73)$$

$$R_d = \frac{L_{gd}}{qW\mu_{rd}\sigma} \left(1 + \zeta_{rd} \left(\frac{\mu_{rd}(V_d - V_{di})}{v_{satd}L_{gd}} \right)^2 \right)^{\frac{1}{2}} \quad (2.74)$$

where L_{gs} (L_{gd}) is the gate to source (gate to drain) access region length, μ_{rs} (μ_{rd}) is the source (drain) access region mobility, v_{sats} (v_{satd}) is the saturation velocity

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in the source (drain) access region, ξ_{rs} and ξ_{rd} are tuning parameters. The parameter extraction of these parameters will be explained in the next chapter.

As in conventional CMOS device, apart from extrinsic source/drain resistance, another intrinsic channel resistance is also considered. However, for simplicity, the intrinsic resistance (r_{ic}) is considered as a part of the source/drain extrinsic resistance with $R_c (=R_e + r_{ic})$ where $r_{ic} = r_{is}$ or r_{id} based on source or drain side, respectively. One can implement this as bias-dependent intrinsic resistance, which will be considered as part of future work.

2.4.7 Self-heating Effects

HEMT devices are usually used in high power electronic applications. It is important to add the self-heating effect [55]–[57] in the core model. The temperature dependent mobility model and the saturation velocity model are given as

$$\mu_1(T_0 + \Delta T) = \mu_1(T_0) \left(\frac{T_0}{T_0 + \Delta T} \right)^2 \quad (2.75)$$

$$v_{sat}(T_0 + \Delta T) = v_{sat}(T_0) \frac{1 + 0.8e^{T_0/600}}{1 + 0.8e^{(T_0 + \Delta T)/600}} \quad (2.76)$$

where $T_0 = 300$ K is the room temperature. $\mu_1(T_0)$ and $v_{sat}(T_0)$ are the fitting parameters extracted at the room temperature. The increase in temperature, ΔT is related to the thermal resistance, R_{th} , and is expressed as

$$\Delta T = R_{th} \cdot |I_{ds}(V_d - V_s)| \quad (2.77)$$

where R_{th} is used as a fitting parameter in the model.

2.4.8 Validation with TCAD and experimental data

To validate the above drain current model, AlGaIn/GaN-HEMTs with gate lengths $L_g=10\ \mu\text{m}$ (long channel) and $L_g=0.25\ \mu\text{m}$ (short-channel) with various access region lengths L_{gs} and L_{gd} values have been simulated using TCAD. L_{gs} and L_{gd} are varied from $0.1\ \mu\text{m}$ to $5\ \mu\text{m}$ to validate the access region length scalability. For the purpose of TCAD simulation, a fixed polarization charge density of $6.8\times 10^{12}\ \text{cm}^{-2}$ is considered at the hetero-interface, with an AlGaIn barrier thickness of 18nm. The CM (Xsim) characteristics are compared with the corresponding TCAD data and they are found to scale with L_{gs} and L_{gd} as well as L_g parameters without any refitting. L_{gs} and L_{gd} scalabilities with various combinations at long- ($L_g = 10\ \mu\text{m}$) and short-channel ($L_g = 0.25\ \mu\text{m}$) are shown in Figs. 2.12 and 2.13, respectively, for the I_{ds} - V_{ds} ($V_{gs}=0\text{V}$) and I_{ds} - V_{gs} ($V_{ds}=2\text{V}$) characteristics. A scalable CM for GaN-HEMTs have been shown and validated with TCAD. The linear ($I_{ds,lin}$) and saturated ($I_{ds,sat}$) drain current degradation with L_{gd} and L_{gs} scaling respectively have been well captured by the CM. A detailed step-by-step procedure to extract the related parameters will be discussed in the next chapter.

Also, the above model is verified with measurement data from AlGaIn/GaN HEMT. The device structures [5] were grown on 4-in. HR-Si (111) substrates with a heterostructure consisting of GaN (2 nm) cap layer/ $\text{Al}_{0.26}\text{GaIn}$ (18 nm) barrier layer/i-GaN (800 nm)/buffer GaN (1400 nm)/AlN ($\sim 100\ \text{nm}$) nucleation layer/Si (111). The cap, barrier, and i-GaN layers are unintentionally doped. The device dimensions are gate-to-source distance (L_{gs}) = $2\ \mu\text{m}$, gate length (L_g) = $2\ \mu\text{m}$, gate width (W_g) = $80\ \mu\text{m}$, and different gate-to-drain distance (L_{gd}) from $2\ \mu\text{m}$ to $10\ \mu\text{m}$. The g_m -degradation

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for increasing L_{gd} is captured by the model as seen from g_m - V_{gs} and I_{ds} - V_{ds} curve in the linear region in Fig. 2.14. The negative slope of the I_{ds} - V_{ds} curve at higher V_{ds} due to the self-heating effects is also exhibited by the model.

The I_{ds} model, together with the 2DEG model, was also applied to the measurement data from MIS-HEMT devices [3]. The sample MIS-HEMT has 8.8-nm of HfO_2 dielectric, a 2.5-nm GaN cap layer, a 18-nm AlGaN barrier layer, a 2.4- μm GaN layer, and nucleation layer on a high-resistivity Si substrate. The measured device has a 0.25- μm gate length and a 50- μm gate width. The same core model can be used for MIS-HEMT devices by modifying the C_d and V_{off} expression of (2.13) and (2.14), respectively. The L_{gs} and L_{gd} lengths are 0.8 μm and 1.6 μm , respectively. The model comparisons with measured data are shown in Figs. 2.15. As seen in Fig. 2.15 (a), there is a significant degradation of I_{ds} at the onset of saturation region for low V_{gs} of -2V, not captured by the model. This is due to the trapping effects from the previous DC sweep of $V_{gs}=-3\text{V}$ and -4V. GaN HEMT in off-state will result in gate- and drain-lag effects. It has been tested that if V_{ds} sweep is limited to lesser voltage ($\sim 10\text{V}$), this current degradation is no longer present. Details of gate-lag effect will be discussed in chapter 4. Nonetheless, the good match, including the transconductance and its smooth derivative, confirms the physics built into the model. These results demonstrate that the proposed surface potential based I_{ds} model can match electrical behaviours of generic HEMTs/MIS-HEMTs devices from subthreshold to strong inversion region with good scalability of gate length as well as source/drain access region lengths.

Fig. 2.12: Simulated (a) I_{ds} - V_{gs} and (b) I_{ds} - V_{ds} characteristics (symbol) for the long channel ($L_g=10 \mu\text{m}$) HEMT, compared with the model (solid line) for different combination of access region lengths L_{gs} and L_{gd} .

Fig. 2.13: Simulated (a) $I_{ds} - V_{gs}$ and (b) $I_{ds} - V_{ds}$ characteristics (symbol) for the short channel ($L_g = 0.25 \mu\text{m}$) HEMT, compared with the model (solid line) for different combination of access region lengths L_{gs} and L_{gd} .

(a)

(b)

Fig. 2.14: Measured (a) $I_{ds} - V_{gs}$ and (b) $I_{ds} - V_{ds}$ characteristics (symbol) of AlGaIn/GaN HEMT with $L_g = 2 \mu\text{m}$, compared with the model (solid line) for different drain access region lengths L_{gd} . The transconductance g_m and the output conductance g_{ds} are also shown showing good scalability with L_{gd} .

Fig. 2.15: Measured (a) I_{ds} - V_{ds} and (b) I_{ds} - V_{gs} characteristics (symbol) for the 0.25-μm MIS-HEMT, compared with the model (solid line) (c) Corresponding first- and second-order derivatives w.r.t. V_{gs} . [3]

2.5 Unified regional charge model

The charge model for AlGaIn/GaN HEMTs was obtained from the Ward-Dutton partition model [58] and derived similar to symmetric bulk-charge linearization. The terminal charge model Q_s and Q_d can be expressed in terms of explicit surface potential, given by [50]

$$Q_d = -\frac{C_d}{2} \left[\overline{V_{gt}} - \frac{\Delta\phi_s}{6} \left(1 - \frac{\Delta\phi_s}{2H} - \frac{\Delta\phi_s^2}{20H^2} \right) \right] \quad (2.78)$$

$$Q_s = -\frac{C_d}{2} \left[\overline{V_{gt}} + \frac{\Delta\phi_s}{6} \left(1 + \frac{\Delta\phi_s}{2H} - \frac{\Delta\phi_s^2}{20H^2} \right) \right] \quad (2.79)$$

$$Q_g = -(Q_s + Q_d) \quad (2.80)$$

where

$$H = \overline{V_{gt}} + v_{th} \quad (2.81)$$

$$\Delta\phi_s = \phi_{s,d} - \phi_{s,s} \quad (2.82)$$

From trans-capacitance definition,

$$C_{ij} = \delta_{ij} \frac{\partial Q_i}{\partial V_j}, \quad \delta_{ij} = \begin{cases} 1 & (i = j) \\ -1 & (i \neq j) \end{cases} \quad (2.83)$$

The model is simpler to bulk MOSFET as bulk charge is not considered due to undoped GaN buffer. The charge model is validated with TCAD for different combinations of L_{gs} and L_{gd} and the total gate capacitance variation for a long channel device, as shown in Fig. 2.16. Both linear and saturation conditions are considered.

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The variation of different capacitance components C_{ij} vs. V_{ds} with L_{gs} and L_{gd} as parameter is shown in Fig. 2.17 (a)-(b). Short ($0.1 \mu\text{m}$) and long ($5 \mu\text{m}$) L_{gs} and L_{gd} are considered in Fig. 2.17(a) and (b) respectively for long channel ($10 \mu\text{m}$) HEMT device. Model symmetry and accuracy have been demonstrated. Overall, a good match with TCAD is obtained. It can be seen that under saturation condition for long access region lengths, the C_{ds} and C_{dg} are under- and over-estimated, respectively by the model, which requires further investigation.

Fig. 2.16: Simulated C_{gg} vs. V_{gs} in linear and saturation region (symbols), fitted with the charge model (lines) for different combinations of access region lengths L_{gs} and L_{gd} .

Fig. 2.17: Simulated C_{ij} vs. V_{ds} (symbols) with $V_{gs} = -1.5\text{V}$, fitted with the charge model (lines) for different combinations of access region lengths L_{gs} and L_{gd} .

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With the dc/ac model implemented for the intrinsic core model, together with some models for parasitic and fringing capacitances, the cut-off frequency (f_T) of a GaN-HEMT can be obtained by running ac analyses over frequency at various gate/drain biases (Q -points) and extracting f_T at the unity current gain ($|i_{out}/i_{in}| = 1$) from the compact model data. The same approach can be used to obtain f_T from the TCAD data for comparison. f_T can also be estimated from [59]

$$f_T = \frac{g_m}{2\pi C_{gg}} \quad (2.84)$$

where g_m is the transconductance, and C_{gg} is the total gate capacitance. Cut-off frequencies are extracted at unity current gain based on the f_T definition. The Verilog-A model is run in commercial SPICE. CM results are shown in Fig. 2.18 and compared with the TCAD data extracted in the same way for a GaN

Fig. 2.18: Modeled f_T vs. V_{gs} at various V_{ds} extracted from the CM data (open symbols), compared with the TCAD data (solid symbols) and Eq. (2.84) (lines)

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HEMT of $L_g=10\mu\text{m}$ and L_{gs} and $L_{gd}=0.1\mu\text{m}$. Results from the simple f_T equation (2.84) are also shown for comparison, in which g_m and C_{gg} are obtained from the CM at the given Q-points. It is seen that the CM has captured the essential high-frequency behaviors in the 2D numerical devices, and the simple formula with the physical CM parameters can be used for quick evaluations and Q-point optimization.

2.6 I-V Model considering GaN buffer doping

The previous sections presented a surface potential based drain current model for generic HEMT devices. The model was based on the URSP approach where analytical expressions of $n_s(V_g)$ and Fermi potential $E_f(V_g)$ were developed that covers strong- and moderate-inversion and subthreshold region of operation. All the existing compact models for HEMT devices follow the n_s expression with two sub-bands in the triangular well given by (2.10). Through Gauss' law, one can relate n_s in (2.10) to the gate (V_g) and channel (V_c) voltages as

$$n_s = \frac{C_d}{q} (V_g - V_{\text{off}} - V_c - E_f) = \frac{C_d}{q} (V_g - V_{\text{off}} - \phi_s) \quad (2.85)$$

where C_d is an effective capacitance (per unit area) between the gate and 2-DEG and V_{off} is the cutoff voltage below which it is in “subthreshold” conduction [60]. The surface potential ϕ_s in V, is referenced to the Fermi level in the body with channel voltage $V_c = V_s$ or V_d at the source or drain ends ($y = 0$ or L_g), respectively, given by

$$\phi_{s1}(V_c) = V_c + E_f(V_c) \quad (2.86)$$

Fig. 2.19: Simulated E_f versus V_{gs} from TCAD using Boltzmann statistics and coupled P-S solution compared with the E_f computed from (2.10)-(2.13). Corresponding derivatives of the E_f solutions w.r.t. V_{gs} is also plotted showing that slope is less than unity in the subthreshold region for P-S solution in contrast to E_f from (2.10)-(2.13)

The GaN HEMT CM presented in previous section along with other existing CMs consider (2.10), (2.85) and (2.86) as the base equation to obtain the explicit expression of surface potential. Although these models are scalable with most of the primary device parameters, they fail to capture the effect of GaN buffer doping (N_a) with corrects built-in physics. There are several reports about non-desirability of “undoped or unintentionally doped” buffer in GaN HEMTs [61], [62]. Inclusion of deep-level dopants in the GaN buffer is necessary to control bulk leakage/ short channel effects (SCEs) [63], [64]. Thus for short channel HEMT devices, capturing model dependency on N_a is very much necessary. A comparison of E_f w.r.t V_g computed from (2.10)-(2.12) and that from coupled P-S numerical simulation in TCAD of a GaN HEMT with $N_a = 5 \times 10^{16} \text{ cm}^{-3}$ is shown in Fig. 2.19. The E_f solution considering Boltzmann

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approximation as used for metal-oxide-semiconductor (MOS) system is also shown along with the first-order derivative of E_f w.r.t V_g . There are two main differences between (2.10) and coupled P-S solution: firstly, a considerable V_{off} -shift is observed when doping is considered compared to (2.10) which does not have N_a dependent term and secondly, the first order derivatives w.r.t V_g in the subthreshold region are different. Although one can fit (2.10) with coupled P-S solution by tuning V_{off} , the discrepancy in the first-order derivative in the subthreshold region cannot be fixed. As (2.10) does not consider any bulk charge term based on N_a and is fully based on inversion charge, the first-order derivative in the subthreshold region is always ~ 1 . Whereas, coupled P-S solution considering both bulk charge and inversion charge result in surface potential slope less than unity in the below- V_{off} region. Apart from this, the referencing of surface potential to the Fermi level in the body (ϕ_s) as shown in (2.86) is also different from the conventional MOS system where surface potential is referenced to the intrinsic Fermi level E_i or the conduction band E_c . The surface potential referencing in (2.86) is physically inaccurate as it will never capture the effect of GaN buffer doping on the surface potential as shown in Fig. 2.20 where the band energy diagram across the AlGaIn/GaN heterostructure interface is shown for $N_a = 5 \times 10^{16} \text{ cm}^{-3}$. The actual surface potential ϕ_{sa} must be referenced to the conduction band E_c in the body, so that it takes into consideration the term ϕ_F which is the difference between the Fermi level E_F and the intrinsic potential E_i . Thus, using (2.10) & (2.86) as the base equations for computing subthreshold surface potential is not accurate.

Fig. 2.20: Energy-band diagram of AlGaN/GaN heterostructure for $N_a = 5 \times 10^{16} \text{ cm}^{-3}$, showing the relation between actual surface potential (ϕ_{sa}) and the Fermi potential (E_f).

A coupled P-S solution considering the dopant charge term will obviously result in a complex implicit charge equation. It is also evident that the bulk charge term only becomes dominant in the subthreshold region when n_s is very low, associated with weak quantum-mechanical effects. So instead of (2.10), it is proposed that the classical charge-voltage equation similar to that in MOS system [34] can be used to obtain the subthreshold surface potential. This claim is strengthened by Fig. 2.19 where a comparison of E_f from coupled P-S solution and Boltzmann approximation is shown. It is observed that below V_{off} when $(E_c - E_f) > 3kT$, the coupled solution and that obtained from Boltzmann approximation match accurately. So by using the simpler Boltzmann approximation instead of (2.10), one can model the V_{off} -shift as well as the correct $E_f(V_g)$ first-order derivative.

A correct surface potential referencing is also necessary to capture the

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effects of bulk charge N_a . Referencing the new actual surface potential ϕ_{sa} to the conduction band in the body, (2.86) can be re-written as

$$n_s = \frac{C_d}{q} (V_g - V_{\text{off}} - V_c - E_f) = \frac{C_d}{q} (V_g - V_{\text{FB}} - \phi_{sa}) \quad (2.87)$$

where V_{FB} is the flatband voltage in HEMT and is given by

$$V_{\text{FB}} = V_{\text{off}} - \phi_F - 0.5E_g \quad (2.88)$$

$$\phi_F = v_{\text{th}} \log(N_a / n_i) \quad (2.88a)$$

where E_g is the GaN energy band-gap, and n_i is the intrinsic carrier concentration. The new surface potential ϕ_s is related to the Fermi potential E_f as given by

$$\phi_{sa}(V_c) = V_c + E_f(V_c) + \phi_F + 0.5E_g \quad (2.89)$$

In the following section, a physics-based approximate single-piece solution for E_f and then ϕ_{sa} from (2.89) for GaN heterostructure will be presented which covers subthreshold as well as moderate- and strong-inversion region. The subthreshold ϕ_{sa} will be computed from classical charge-voltage equation that incorporates bulk charge N_a , whereas ϕ_{sa} in the moderate and strong inversion will be based on coupled P-S solution. Based on the proposed $\phi_{sa}(V_g, V_c)$ model, a continuous current-voltage model is formulated. The unified compact model is validated with the simulated as well as measured GaN HEMT data.

2.6.1 Piecewise explicit regional surface potential solution

(a) Subthreshold region ($V_{go}=V_g-V_{off} < 0$)

As discussed earlier, it is physically justified to consider classical charge-voltage equation in the subthreshold region for HEMT devices. We adapted the asymptotic regional surface potential (depletion approximation) in subthreshold region developed for bulk-nMOS system as given by [34]

$$\phi_{sub} = \left(-\frac{\Upsilon}{2} + \sqrt{\frac{\Upsilon^2}{4} + \mathcal{G}_f(V_{gf}; \varepsilon)} \right)^2 \quad (2.90)$$

$$\mathcal{G}_f(x; \sigma) = 0.5 \left(x + \sqrt{x^2 + 4\varepsilon} \right) \quad (2.90a)$$

where $V_{gf} = V_g - V_{FB}$ is defined as the “flatband-shifted” gate voltage, ε is the smoothing parameter and Υ is the “body factor” given by

$$\Upsilon = \sqrt{2q\varepsilon_{uid}N_A} / C_d \quad (2.91)$$

where q is the electron charge, ε_{uid} is the unintentionally doped GaN buffer permittivity. As the previous model in section 2.4 [3] was based on regional solution of Fermi potential (E_f) and not on surface potential, it is necessary to convert ϕ_{sub} to $E_{f,sub}$ by using (2.89) before we proceed to get the unified E_f model.

$$E_{f,sub} = \phi_{sub} - V_c - \phi_F - 0.5E_g \quad (2.92)$$

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(b) Moderate-inversion region ($E_f < E_0$ and $V_{go} > 0$)

In moderate inversion, regional E_f solution is given by [3]

$$E_{f,mod} = V_{go} - \frac{V_{th}}{1 + \lambda_0} \mathcal{L} \left\{ \theta e^{(1+\lambda_0)V_{go}/V_{th}} \right\} \quad (2.93)$$

$$V_{go,act} = 0.5 \left(V_{go} + \sqrt{V_{go}^2 + 4\varepsilon} \right) \quad (2.93a)$$

where ε is a smoothing parameter, λ_0 and θ are device dependent parameters, defined in section 2.3.

(c) Strong-inversion region ($E_f > E_0$)

A unified E_f model for the strong-inversion region can be obtained, similar to previous model as [3]

$$E_{f,str} = \mathcal{M} \cdot V_{go,act} \quad (2.94)$$

$$\begin{aligned} \mathcal{M} &= \mathcal{G}(\mathcal{M}_1, \mathcal{M}_0; \alpha) \\ &= 0.5 \left(\mathcal{M}_1 + \mathcal{M}_0 + \alpha - \sqrt{(\mathcal{M}_1 - \mathcal{M}_0 - \alpha)^2 + 4\alpha\mathcal{M}_1} \right) \end{aligned} \quad (2.94a)$$

where α is a smoothing parameter, $\mathcal{M}_0$ and $\mathcal{M}_1$ are defined in section 2.3.

2.6.2 The 2DEG n_s and E_f unified models

(a) Moderate to strong-inversion (“active”) region

Based on two additional parameters subthreshold voltage ($V_{g,SUB}$ with $E_f=0$) and the critical voltage ($V_{g,CR}$ with $E_f=E_0$), a unified E_f expression that is valid from moderate to strong-inversion regions, namely, the “active region,” the following interpolation function is used [3]

$$E_{f,act} = \frac{2\mathcal{M}_{eff}V_{go,CR} \ln\left(1 + e^{V_{go,act}/2V_{go,CR}}\right)}{1 + \frac{\ln\left(1 + e^{V_{go,sub}/2V_{go,CR}}\right)}{E_{f,mod} / (2\mathcal{M}_{eff}V_{go,CR})} e^{(V_{go,sub}-V_{go,act})/2V_{go,CR}}} \quad (2.95)$$

where $V_{go,sub}=V_g-V_{off}$ is the V_{off} -shifted subthreshold voltage. The regional $E_{f,sub}$ and the unified $E_{f,act}$ solution as an explicit function of V_{gs} are plotted in Fig. 2.21(a) and compared with the exact E_f solution from coupled P-S simulation from TCAD. The differences in the regional models w.r.t. the coupled P-S solution are shown in the inset of Fig. 2.21(a). As expected, $E_{f,sub}$ and $E_{f,act}$ are more accurate in subthreshold and active regions respectively.

(b) Unified single-piece solution

A single-piece explicit E_f expression that is valid in all regions can be obtained by joining $E_{f,act}$ in (2.95) and $E_{f,sub}$ in (2.92) through the use of an interpolate function. The simplest way is to use to conventional square root interpolation function given by

$$E_{f1} = 0.5 \left(E_{f,act} + E_{f,sub} + \Gamma - \sqrt{(E_{f,act} - E_{f,sub} - \Gamma)^2 + 4\Gamma E_{f,act}} \right) \quad (2.96)$$

where Γ is a smoothing parameter. The unified solution E_{f1} w.r.t V_{gs} shown in Fig. 2.21(a) seems to match well with the coupled solution as visually observable. However, E_{f1} solution was found to be not so accurate in the near- V_{off} region due to the square-root term in (2.96). Another way to connect $E_{f,act}$ and $E_{f,sub}$ is the log-exponential interpolation function given by

Fig. 2.21: (a) Regional E_f solutions versus V_{gs} : Moderate to strong inversion (“active”) region $E_{f,act}$ [solid line, (2.95)], subthreshold $E_{f,sub}$ [long-dashed line, (2.92)], and single piece unified E_f computed from (2.96) [line-crosses], and (2.97) [dashed-dotted] compared with the exact E_f [circles] from P-S solution. (b) Corresponding derivatives of the unified E_f solutions w.r.t. V_{gs} computed from both (2.96) and (2.97) compared with TCAD P-S solution.

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$$E_f(V_c) = E_{f,\text{sub}}(V_c) - \Delta E_f \quad (2.97)$$

$$\Delta E_f = \frac{2\rho \left(1 - \frac{E_{f,\text{act}}}{E_{f,\text{subACT}}}\right) \ln\left(1 + \exp(E_{f,\text{sub}} / 2\rho)\right)}{1 + \tilde{C}_d \left(1 - \frac{E_{f,\text{act}}}{E_{f,\text{subACT}}}\right) \exp(-E_{f,\text{sub}} / 2\rho)} \quad (2.97a)$$

$$E_{f,\text{subACT}} = 0.5 \left(E_{f,\text{sub}} + \sqrt{E_{f,\text{sub}}^2 + 4\varepsilon_1} \right) \quad (2.97b)$$

where ρ and ε_1 are smoothing parameter. It is seen that (2.97) approaches $E_{f,\text{act}}$ when $E_{f,\text{sub}} \gg 2v_{th}$ in the active region, and for $E_{f,\text{sub}} \ll 2v_{th}$, (2.97) approaches $E_{f,\text{sub}}$ when in the subthreshold region. It is worth mentioning that $E_{f,\text{subACT}}$ is used instead of $E_{f,\text{sub}}$ in (2.97a), to avoid discontinuity when $E_f \sim 0$ in the near- V_{off} region.

A comparison of the two unified solution, E_{f1} (2.96) and E_f (2.97) with the exact E_f solution computed from P-S solution is shown in Fig. 2.21(a). E_f from (2.97) results in overall less error compared to (2.96) as shown in the inset. The corresponding derivatives w.r.t. V_{gs} are plotted in Fig. 2.21(b), showing the model smoothness. First order derivative of E_f (2.96) w.r.t. V_{gs} also matches well with the exact solution whereas the E_{f1} (2.97) fails to capture the accuracy and smoothness in the near- V_{off} / moderate inversion region due to the nature of the square-root interpolation function. Once an explicit unified E_f model (2.96) is developed, a compact surface-potential model is available from (2.89), which can be used in a surface potential based terminal current/charge model. The drain current is then given by

$$I_{\text{ds}} = \beta \left(q_i + v_{\text{th}} \overline{A_b} \right) V_{\text{ds}} \quad (2.98)$$

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where $\beta = W\mu C_d/L_{\text{eff}}$ is the gain factor,

$$\overline{q_i} = (V_{\text{gt},s} + V_{\text{gt},d})/2 \quad (2.99)$$

$$V_{\text{gt},c} = E_{f,\text{sub}} - E_f(V_c) = \Delta E_f(V_c) \quad (2.100)$$

$$\overline{A_b} = 1 + \frac{\Upsilon}{2\sqrt{\phi_s}} \quad (2.101)$$

$$\overline{\phi_{\text{saeff}}} = (\phi_{\text{saeff},s} + \phi_{\text{saeff},d})/2 \quad (2.102)$$

where $\phi_{\text{saeff},c} \equiv \phi_{\text{sa}}(V_{c,\text{eff}})$ with $c = s/d$ for S/D, and from (2.89) and (2.97), it is given by

$$\begin{aligned} \phi_{\text{saeff},c} &= V_{c,\text{eff}} + E_f(V_{c,\text{eff}}) + \phi_F + 0.5E_g \\ &= E_{f,\text{sub},c} + \Delta E_f(V_{c,\text{eff}}) + \phi_F + 0.5E_g \quad (c = s, d) \end{aligned} \quad (2.103)$$

The effective source/drain voltage, the average electric field and the effective mobility equations have already been discussed in section 2.5. It is to be noted that the second term in E_{eff} in (2.55) is no longer ignored as Υ has non-zero value when N_a considered. A comparison of the normalized inversion charge $V_{\text{gt},s}$ (2.100) w.r.t V_{gs} obtained from (2.96) and (2.97) is shown in Fig. 2.22. Although in active region, (2.96) and (2.97) result in comparable errors, (2.96) gives erroneous slope of the $V_{\text{gt},s}$ in the subthreshold region even for different values of the smoothing parameter Γ . This proves that for unified E_f solution as well I-V modeling, (2.97) is the correct choice. This analysis also shows that it is always necessary to validate not only E_f but also the inversion charge n_s in terms of errors and model smoothness.

Fig. 2.22: Comparison of normalized inversion charge V_{gts} computed from (2.96) and (2.97). V_{gts} computed from (2.96) for different Γ fails to capture the correct subthreshold slope compared to that computed from (2.97).

The unified E_f model (lines) versus V_{gs} , compared with the exact solutions (symbols), and model scaling with the GaN buffer doping ranging from 0 (fully-undoped) to 10^{17} cm^{-3} is shown in Fig. 2.23(a). The differences (or absolute errors) between the model and the exact solution is plotted in the inset, showing an overall error below $\sim 5 \text{ mV}$. The corresponding derivatives of E_f w.r.t. V_{gs} are shown in Fig. 2.23(b), demonstrating the model smoothness. The developed E_f model is scalable with buffer doping as well as other major device parameters with errors in the millivolt range. The degradation of the first order derivative of E_f with increasing N_a in the subthreshold region has been well captured by the regional surface-potential based model, owing to the incorporation of buffer doping dependent regional E_f solution.

(a)

(b)

Fig. 2.23: (a) Unified E_f solutions [solid line] versus V_{gs} compared with the exact solutions [symbols] for different GaN buffer doping. Inset: Absolute error (difference) between the unified E_f model and the exact E_f solution. (b) Corresponding derivatives of E_f w.r.t. V_{gs} .

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The I_{ds} model (2.98) is validated with TCAD for long ($10\mu\text{m}$) and short ($0.25\mu\text{m}$) channel length devices as shown in Fig. 2.24(a) and (b) respectively. Low (10^{15}cm^{-3}) and high ($5\times 10^{16}\text{cm}^{-3}$) GaN buffer doping are considered to demonstrate the effects of doping on subthreshold slope at different V_{ds} . Long-channel HEMTs suffer from slight threshold voltage roll-off but not significant subthreshold slope degradation with V_{ds} , even at low buffer doping of 10^{15}cm^{-3} as shown in Fig. 2.24(a). However, lightly doped short-channel GaN HEMTs exhibit severe threshold voltage roll-off as well as subthreshold slope degradation at high V_{ds} as shown in Fig. 2.24(b). The proposed model considering GaN buffer doping along with the DIBL model in section 2.5.5 together now represents a correct short channel effect model. As the channel length continues to decrease and when $V_{ds}\neq 0$, the minimum potential occurs at $y=y_{\min}$ (2.71), where $y_{\min}$ is dependent on the GaN buffer doping. The model can be played back by tuning the doping level to fit the accurate subthreshold slope at high V_{ds} , which is a unique behavior of the proposed model. A step-by-step parameter extraction procedure for short channel devices is presented in the next chapter. The presented model is able to predict both long and short channel device characteristics with any buffer doping level due to accurate regional E_f solutions.

The model is also fitted with experimental I_{ds} - V_{gs} and I_{ds} - V_{ds} obtained from $0.105\mu\text{m}$ $\text{In}_{0.13}\text{Al}_{0.83}\text{Ga}_{0.04}\text{N}/\text{GaN}$ HEMT, as shown in Fig. 2.25 (a) and (b) respectively. The heterostructure consisted of a 10.8-nm quaternary $\text{In}_{0.13}\text{Al}_{0.83}\text{Ga}_{0.04}\text{N}$ barrier layer and 0.5 nm AlN interlayer as the top barrier and a $1.8\mu\text{m}$ GaN buffer [65]. The model uses these physical parameters to predict the device characteristics. As our base model considers physical expression of

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V_{off} and C_g , it can be used for any III-V heterostructure system. The subthreshold slope degradation with increasing V_{ds} has been nicely captured by the surface-potential-based SCE model as shown in Fig. 2.25(a). However, if (2.10) is used for n_s-E_f formulation, which does not consider GaN buffer doping, capturing the subthreshold slope degradation would not have been possible based on surface-potential-based approach. Since the current model has the unique feature of realizing classical charge-voltage equation with buffer doping in the subthreshold region and coupled P-S solution in the moderate- and strong-inversion region, it was possible to accurately model the subthreshold as well as ON-state drain current characteristics in short-channel devices. It is concluded that although the existing HEMT CMs do not consider buffer doping in the surface-potential formulation, it does play a considerable role in the subthreshold region even if the buffer is “unintentionally doped”. The compact model presented in this section shows its scalability over major device parameters and can be used to predict HEMT device behavior for any material system.

(a)

(b)

Fig. 2.24: Modeled I_{ds} - V_{gs} characteristics (lines) for (a) long- ($10\ \mu\text{m}$) and (b) short-channel ($0.25\ \mu\text{m}$) AlGaIn/GaN HEMT shown, compared with the numerical simulation (symbols) for different GaN buffer doping. In contrary to long channel devices, the short channel HEMTs suffer from DIBL and subthreshold slope degradation at high V_{ds} due to thick-body-effects which was captured by the new model.

Fig. 2.25: Measured (a) I_{ds} - V_{gs} and (b) I_{ds} - V_{ds} characteristics (symbol) for the 0.105- μm $\text{In}_{0.13}\text{Al}_{0.83}\text{Ga}_{0.04}\text{N}/\text{GaN}$ HEMT shown, compared with the model (solid line). The subthreshold slope degradation with V_{ds} has been well captured by incorporating the finite bulk charge term in the n_s - E_f model.

2.7 Gate leakage model of HEMTs

In the past few years, considerable efforts have been made to fabricate high quality Schottky contacts on AlGaN/GaN heterostructures which poses a serious challenge due to normally high gate leakage. As GaN HEMT devices are normally ON devices with high 2-DEG concentration, large negative bias is necessary to turn off the device, thus standby power dissipation becomes a serious reliability concern [66]–[68]. While the forward leakage is caused mainly due to Schottky contact, the reverse leakage is more due to trapping/detrapping effects caused by Poole-Frenkel (PF) effects [6]. The following section presents a simpler approach to model both the forward and reverse leakage currents in AlGaN/GaN HEMTs.

2.7.1 Forward leakage model

Ideally, the forward leakage in AlGaN/GaN heterostructure is caused by Schottky transport in contrast to p-n junctions where diffusion transport takes place. However, there are several other non-ideal factors which contribute to the

Fig. 2.26: Different mechanisms for forward gate leakage: 1. Thermionic emission (TE) 2. Trap assisted tunneling (TAT) 3. Generation-Recombination (GR) [4]

Fig. 2.27: Forward gate leakage components: TAT and edge leakage [Dashed], TE and GR component [Dotted] fitted with the measured data [Symbols] of AlGaIn/GaN diode. The sum of all the 4 components [solid line] fitted nicely with measured data.

forward gate current as shown in Fig. 2.26. Apart from the thermionic emission (TE) of electrons over the potential barrier, other factors such as generation-recombination of electron-hole pairs in defect centres (GR) and tunneling of electrons through distributed trap centres (TAT) also lead to forward leakage. Measured forward gate leakage on AlGaIn/GaN diodes is shown in Fig. 2.27 at temperature $T=373\text{K}$. It is seen that the slope abruptly changes at $V_g \sim 0.75\text{V}$ supporting the claim that thermionic emission is not the dominant mechanism for forward gate leakage.

The initial slope of the forward I-V curve at lower voltage is less steep and should not be due to TE. Several reports indicate that this low level of current should come from TAT transport through trap centres in the AlGaIn and the current density is given by [61, 62]

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$$J_{\text{TAT}} = J_T \exp\left(\frac{q(V - IR_s)}{E_o}\right) \quad (2.104)$$

where J_T is the saturation tunneling current density, E_o is the characteristic energy, and R_s is the series resistance of the diode. Also at a very low forward bias, edge leakage current becomes dominant, and is given by [61]

$$I_R = \frac{V - IR_s}{R_{\text{sh}}} \quad (2.105)$$

where R_{sh} is the shunt resistance which can be obtained from the reverse I - V characteristics of the diodes at low gate bias.

When the applied gate bias increases beyond 0.75V, the slope changes abruptly and the curve can be better fitted by considering the TE mechanism. In this region, the current flow is fully dominated by barrier height and independent of heterostructure junction profile such as depletion width, etc. The TE current from the GaN to the metal is then given by [61]

$$I_{\text{TE}} = I_0 \left(e^{\frac{(V - IR_s)}{\eta_F kT}} - 1 \right) \quad (2.106)$$

$$I_0 = AA^* T^2 e^{-\frac{q\Phi_B}{kT}} \quad (2.106a)$$

where A is the contact area, A^* is the effective Richardson constant, n_F is the ideality factor and $q\Phi_B$ is the zero-bias barrier height. Ideally, n_F should be equal to unity, However, due to combination of different mechanisms for gate-leakage, n_F often is greater than unity when only TE is considered. (2.106) is an implicit function of the gate current, which, by using the *Lambert W* function, $L\{w\}$, can be explicitly expressed as

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$$I_{TE} = \frac{\eta_F v_{th}}{R_s} L \left\{ I_0 R_s e^{\frac{(V + I_0 R_s)}{\eta_F kT}} \right\} - I_0 \quad (2.107)$$

Apart from TE, another mechanism that can dominate the high-bias forward leakage is the generation-recombination (GR) process in the depletion region, given by

$$I_{GR} = \frac{A q n_i W_d}{2 \tau_{rc}} \exp \left(\frac{q(V - I R_s)}{2 kT} \right) \quad (2.108)$$

$$\tau_{rc} = (\sigma v_n N_{tr})^{-1} \quad (2.108a)$$

where W_d is the depletion width, τ_{rc} is the effective carrier lifetime, σ_c is the capture cross-section, v_n is the thermal velocity, and N_{tr} is the recombination centre concentration. The total forward gate leakage is then given by the sum of (2.104)-(2.108). The sum of TAT current component and the edge leakage component is fitted with the measured data in the low bias region, as shown in Fig. 2.27. The sum of TE and the GR current component on the other hand is fitted with steep slope part where the series resistance dominates when $V_g > 1V$. It is seen that with regional modeling approach, the gate leakage can be modeled effectively over the entire forward gate bias. The forward gate leakage for different temperature is fitted with the above model and shown in Fig. 2.28. With extracted parameter of $\Phi_B=1.25V$ and ideality factor n_F of unity, the above model is now scalable with temperature. Unity value of n_F also explains that all the different mechanisms of gate leakage have been captured accurately.

Fig. 2.28: Forward gate leakage I_g versus V_g [dashed line] fitted with measurement data [symbols] [5] of AlGaIn/GaN diode for different temperature from 273K to 433K.

2.7.2 Reverse leakage model

As the GaN HEMTs are normally on devices, large negative bias needs to be applied to reach threshold voltage and thus the reverse gate leakage largely affects the standby power dissipation. There has been a wide range of studies on gate leakage in GaN HEMTs [70]–[73], most of which attributes Poole-Frenkel (P-F) emission as the dominant mechanism as shown in Fig. 2.29(a). The motivation for modeling reverse gate-leakage in context of this work is shown in Fig. 2.29(b) where measured 2-terminal reverse current w.r.t gate bias V_g is plotted. It is seen that reverse leakage increases with V_g in the sub- V_{off} region aggressively although not visible from log scale compared to the linear scale plot. Most of the reports plot reverse leakage current in log scale and thus misses its V_g -dependent behavior in the sub- V_{off} region.

Fig. 2.29: (a) Energy diagram of the trapping centre across the AlGaN barrier layer in the presence of the electric field. Arrows indicate the possible mechanisms of electron emission by thermal ionization over the lowered barrier: P-F Emission [6] (b) Reverse gate leakage versus V_g with [solid line] and without [dashed line] considering buffer doping compared with measurement data of AlGaN/GaN diode [symbols] [5]. The P-F based leakage model considering bulk charge is able to capture the non-zero slope of the gate leakage in contrary to the previous model where total charge in the subthreshold region is considered negligible.

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The current density (J_{PF}) corresponding to P-F emission is given by [74]

$$\begin{aligned} J_{\text{PF}} &= C E_b \exp\left(\left(\phi_t - \Delta\phi_{\text{PF}}\right) / v_{\text{th}}\right) \\ &= C E_b \exp\left(\left(\phi_t - \beta_{\text{PF}} \sqrt{E_b}\right) / v_{\text{th}}\right) \end{aligned} \quad (2.109)$$

where C and β_{PF} are constants, ϕ_t is the barrier height for the electron emission from the trap state and E_b is the effective electric field in the barrier given by [74]

$$E_b = (q\sigma - Q_t) / \varepsilon_b \quad (2.110)$$

where σ is the polarization charge density, Q_t is the total charge (per unit area) given by the sum of bulk charge Q_b and 2DEG n_s and is calculated as

$$Q_t = C_d (V_g - V_{\text{off}} - E_f) \quad (2.111)$$

Existing CMs [70] including our base model presented in (2.36) do not consider buffer doping and as a result, no bulk charge term was considered in the formulation. So the electric field E_b in the subthreshold region is nearly constant ($\sim q\sigma/\varepsilon_b$) as Q_t ($\sim n_s$) is very small when V_g is below V_{off} . As reported in [70], reverse leakage is nearly constant in the sub- V_{off} region. However, in the present model (2.97) where GaN buffer doping was considered, Q_t in the subthreshold region equals to bulk charge Q_b given by

$$Q_b = C_d Y \sqrt{\phi_s} \quad (2.112)$$

where Y is the body factor, calculated from the GaN buffer doping concentration. As a result, E_b in the subthreshold region does not saturate but still varies with V_g . A plot of the measured reverse leakage I_g w.r.t V_g at $T=292\text{K}$ [5] is shown in Fig. 2.29(b) and a good match with the model is observed. Gate leakage without considering bulk charge (2.36) is also computed

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and plotted as a comparison to show the improvement of the proposed model. As observed from the linear scale, the new bulk-charge based model can explain the slope of the reverse leakage current nicely compared to base model which shows zero slope of the current. Modeled reverse gate-leakage at different temperature from 273K to 393K compared with measured data is shown in Figs. 2.30 and good temperature scalability can be observed. The non-zero slope of the gate current at different temperatures has been captured by the above model.

The above forward and reverse leakage models are based on 2-terminal diode structures. For 3-terminal HEMT devices, the above model can be extended by considering the surface potential calculation at the source and drain end and recalculating the effective gate leakage with correct V_{ds} dependency.

Fig. 2.30: Modeled reverse gate leakage I_g verses V_g [dashed line] considering buffer doping compared with measurement data of AlGaIn/GaN diode for different temperature from 273K to 393K [symbols] [5].

2.8 Surface potential based I-V model for MIS-HEMTs

As HEMTs suffer from high gate leakage due to metal-semiconductor contact, lot of interest shifted towards the MIS-HEMT structure where the insulator above the AlGa_N barrier results in reduced gate leakage current. The surface potential based model presented in the previous sections can be used for MIS-HEMTs by modifying the V_{off} and C_d expression based on correct energy band diagram as shown in Fig. 2.31(a). However, if the gate voltage is increased above certain voltage $V_{\text{off}2}$, a parallel channel will be formed in the AlGa_N barrier layer which must be taken into account by the compact model. As shown in Fig. 2.31(a), Fermi potential E_f at the 2DEG interface saturates at certain $V_g = V_{\text{off}2}$, and the 2DEG is practically shielded from the control of gate voltage. The TCAD simulated electron concentration contour plot is shown in Fig. 2.31(b) showing the existence of a second channel at the oxide-AlGa_N interface at high V_g . Assuming the barrier layer is undoped, from Gauss Law one can express the variation of the Fermi potential at the insulator-barrier (or cap layer if present) layer interface (surface Fermi Potential) as

$$E_{\text{sf,sub}} = \Phi_{\text{MB}} - \Phi_{\text{SB}} - V_g - \left(q\sigma - C_g (V_g - V_{\text{off}} - E_f) \right) / C_{\text{ox}} \quad (2.113)$$

where C_{ox} is the oxide capacitance, C_g is the total series capacitance of oxide and AlGa_N barrier, Φ_{MB} and Φ_{SB} represent the metal-to-insulator and insulator-to-GaN cap barrier height, respectively and σ is the polarization charge density.

(a)

(b)

Fig. 2.31: (a) Energy band diagram for MIS heterostructure for different V_g showing the formation of second quantum well at the oxide-AlGaN interface when $V_g > 1.5V$. (b) TCAD simulated electron concentration contour for different gate bias. For V_g above 1.5V, a second channel is formed at the top interface apart from the 2DEG.

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When $V_g > V_{\text{off2}}$, the 2DEG Fermi potential E_f saturates ($=E_{f,\text{ss}}$) due to the formation of a second channel. Thus, (2.113), which considers E_f and not $E_{f,\text{ss}}$, can only model the surface Fermi potential in the subthreshold region corresponding to the second channel. So in the compact model formulation, surface Fermi potential can be directly obtained from (2.113) when $V_g < V_{\text{off2}}$. In the active region of operation corresponding to the second channel, from the band diagram, one can derive

$$(\Phi_{\text{MB}} - V_g) + V_{\text{ox}} = \Phi_{\text{SB}} - E_{\text{sf,act}} \quad (2.114)$$

where V_{ox} is the voltage across the insulator, $E_{\text{sf,act}}$ is the surface Fermi Potential in the active region. From (2.114), it can be concluded that $(\Phi_{\text{MB}} - \Phi_{\text{SB}})$ is the effective turn-on voltage V_{off2} above which the second channel is formed. Thus (2.10) can still be used as the base equation for solving $E_{\text{sf,act}}$ when $V_g > V_{\text{off2}}$. The unified surface Fermi potential $E_{f,\text{sf}}$ solution from depletion to strong inversion can thus be written as,

$$E_{f,\text{sf}} = 0.5 \left(\frac{E_{\text{sf,acteff}} + E_{\text{sf,sub}} + \alpha_1}{-\sqrt{(E_{\text{sf,acteff}} - E_{f,\text{sf,sub}} - \alpha_1)^2 + 4\alpha_1 E_{\text{sf,acteff}}}} \right) \quad (2.115)$$

$$E_{\text{sf,acteff}} = 0.5 \left(E_{\text{sf,act}} + \sqrt{E_{\text{sf,act}}^2 + 4\varepsilon_1} \right) \quad (2.115a)$$

where α_1 and ε_1 are smoothing parameters. (2.115a) ensures $E_{\text{sf,act}}$ approaches zero in the subthreshold region of operation corresponding to the second channel. The final solution $E_{f,\text{surf}}$ approaches $E_{\text{sf,acteff}}$ when $V_g > (\Phi_{\text{MB}} - \Phi_{\text{BS}})$ in the moderate and strong inversion region. In the subthreshold condition, $E_{f,\text{sf}}$ follows $E_{\text{sf,sub}}$. The variation of final E_f solution with V_g is shown in Fig. 2.32 for 3 different thickness of insulator where an accurate match with the coupled

Fig. 2.32: The variation of Fermi potential at the oxide/AlGaIn (2.115) and at the 2DEG (2.116) interface fitted with the coupled P-S solution for different insulator thickness. Shown in the inset, the surface Fermi potential $E_{f,sf}$ at the oxide-AlGaIn interface.

P-S solution can be observed. The 2DEG Fermi potential E_f , on the other hand, saturates when $V_g > (\Phi_{MB} - \Phi_{SB})$. One way to obtain the saturated E_f is to iteratively solve (2.36) and (2.113) which will be computationally complex. A simpler way of approximation is to calculate the $E_f (=E_{f,ss})$ at $V_g = (\Phi_{MB} - \Phi_{BS})$ from the regional strong inversion E_f solution (2.20).

The final 2DEG E_f solution is then given by

$$E_{f,eff} = 0.5 \left(\frac{E_{f,ss} + E_f + \alpha_2}{-\sqrt{(E_{f,ss} - E_f - \alpha_2)^2 + 4\alpha_2 E_{f,ss}}} \right) \quad (2.116)$$

where α_2 is a smoothing parameters. The modeled 2DEG Fermi potential $E_{f,eff}$ is also plotted in Fig.2.32 matched with coupled P-S solution and the saturation effect has been nicely captured by the approximate solution. As the second

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channel is due to the variation of surface Fermi potential $E_{f,sf}$, a highly accurate solution of saturated 2DEG $E_{f,ss}$ is not necessary, thus justifying the approximation in (2.113). The above model has been extended to drain current model and fitted with TCAD data for MIS-HEMT devices with 12 nm of Al_2O_3 as insulator. A plot of the modeled I_{ds} - V_{gs} and g_m - V_{gs} fitted with the TCAD data is shown in Fig. 2.33 (a) and (b) respectively. The formation of the second channel in the AlGaN-oxide interface results in a second hump in the g_m - V_{gs} curve at high gate bias which has been nicely captured by the above model.

(a)

(b)

Fig. 2.33: Modeled (a) I_{ds} - V_{gs} and (b) g_m - V_{gs} for $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ MIS-HEMT fitted with numerical simulation (symbols). The second g_m -hump at $V_g \sim 1.6\text{V}$ is captured by the proposed parallel channel model.

2.9 Conclusion

In the first part of the chapter, a single-piece unified model for the 2DEG density and the Fermi potential in the triangular quantum well that is valid from strong-inversion to moderate-inversion and subthreshold regions was developed. The importance of considering the moderate-inversion regional solution was explained from the 2DEG capacitance modeling. The explicit E_f model, which relates to the surface potential ϕ_s , was extended directly to a ϕ_s -based terminal current (and charge) model for generic HEMT compact modeling. The various short-channel effect as well as self-heating effects were incorporated in the drain current model. The model was validated with TCAD as well as measurement data to show full scalability with device geometries.

In the later part of the chapter, focus was given on development of surface potential and corresponding explicit n_s - E_f solution by considering GaN buffer doping. The regional surface potential approach was used to combine quantum mechanics in moderate- and strong-inversion and classical Boltzmann approximation in subthreshold region for GaN HEMT modeling. The new model was validated with numerically simulated surface potential for a wide range of buffer doping with smooth derivatives. The ϕ_s -based terminal current model considering GaN buffer doping along with the DIBL model now forms a correct short-channel-effect model which can capture the subthreshold slope degradation with increasing V_{ds} .

Apart from drain current modeling, forward and reverse gate leakage currents were also modeled for GaN HEMTs. Reverse gate leakage based on P-F emission, which depends mainly on the AlGaIn barrier electric field, was

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modeled and validated with measured data and a considerable improvement was observed compared to the previous model when GaN buffer doping term was incorporated.

For MISHEMT devices, a parallel channel is formed at high gate bias in the AlGa_N barrier layer which was modeled in the last part of this chapter. The proposed model was able to capture the second hump in the transconductance due to parallel channel in oxide-AlGa_N interface for high gate bias.

The combined 2DEG formalism based on quantum physics with ϕ_s -based electrostatics and DD transport has demonstrated advantages in capturing the essential physical behaviors in generic HEMTs and MIS-HEMTs devices. The surface-potential based short-channel model with accurate in-built physical approximations can thus support the circuit designers to explore III-V on Si based circuit designs.

Chapter 3: Extraction of Physical and Model Parameters

3.1. Importance of model parameter extraction

A compact model should not only be physics based and scalable but it also should offer an easy way for parameter extraction. This chapter focuses on the procedures to extract the different physical (d , N_A) as well as smoothing/fitting parameters (ϵ , ϵ_1 , ρ , γ_0 , γ_1 , μ_1 , μ_2 , μ_3 etc.). The extraction procedure in this chapter is based on the model incorporating GaN bulk doping as described in section 2.5. The model extraction procedure is described based on GaN HEMT with the help of SILVACO TCAD data. Similar procedure can be extended to MIS-HEMT model extraction as both share the similar core model equations.

3.2. HEMT charge model extraction

To proceed with charge model extraction, gate capacitance C_{gg} data were generated numerically using known parameters ($d=18\text{nm}$, $N_A=10^{16}\text{cm}^{-3}$) for a long channel HEMT ($L_g=10\mu\text{m}$). It can be seen in Figure 3.1 that the charge model is able to match with depletion capacitance with correct value of substrate doping concentration, while other values fail to match the data.

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Similarly, the strong inversion regional capacitance is well matched with model for correct value of physical AlGaIn thickness ($d=18\text{nm}$) as shown in Figure 3.2. Other AlGaIn thicknesses have either over- or under-estimated the capacitance relative to the TCAD data. In a model, all of the device parameters

Fig. 3.1: The comparison of unified regional model's effective channel doping concentration variation with TCAD data for depletion capacitance.

are essentially effective values that must be extracted from data. So to demonstrate the calibration steps, a long channel C_{gg} data was generated with known values ($d=18\text{nm}$, $N_A=10^{15}\text{cm}^{-3}$). The extraction steps are explained below.

Fig. 3.2: The comparison of unified regional model's effective AlGaN barrier thickness variation with TCAD data for strong inversion capacitance.

Step 1: The model assumes that the initial guess of AlGaN thickness (d) can be estimated from strong inversion C_{gg} data, using $N_A = n_i$. The correct GaN doping concentration can then be extracted by fitting the depletion capacitance with correct slope as shown in Figure 3.3 (a). The extracted N_A ($=9.89 \times 10^{14} \text{cm}^{-3}$) is close to the known value.

Step 2: After depletion capacitance was fitted, calibration was done for the moderate- and strong-inversion region. The AlGaN thickness d can be tuned to fit the full inversion region as shown in Figure 3.3 (b). For $d=17\text{nm}$ and 17.5nm , the C_{gg} curve shift throughout the moderate- and strong- inversion region.

Step 3: The surface potential model in this work is based on the triangular quantum well with 2 sub-bands E_0 and E_1 as mentioned in (2.9), which has 2

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parameters, γ_0 and γ_I , respectively. γ_0 and γ_I also affect the moderate- and strong inversion, respectively, and is given as

$$\gamma_n = c_n \left[\frac{\hbar^2}{2m^*} \left(\frac{q^2}{\epsilon_{\text{uid}}} \right)^2 \right]^{1/3}, \quad n = 0, 1, 2, 3, \dots \quad (3.1)$$

where m^* is the effective mass of electrons in the GaN 2DEG channel, ϵ_{uid} is the GaN permittivity, $\hbar$ is the reduced Plank's constant and c_n is a constant obtained from Airy function. It is known that m^* may not be constant and varies with process conditions and substrate wafer. Also, c_n can vary based on mathematical approximations of the Airy function. Thus, γ_0 and γ_I shall not be considered as fully physical parameters and may need fine tuning to match the C_{gg} data. Thus in step 3, γ_0 is tuned to match the moderate-inversion region (blue line in Figure 3.3(b)).

Step 4: γ_I is tuned to match the strong-inversion region. As shown by pink line in Figure 3.3(b), lower values of γ_I will totally under-estimate the C_{gg} data.

Step 5: d is re-tuned to match the data in the inversion region. The procedure from step 2 to step 4 can be repeated until model is matched to data with satisfactory accuracy. (Extracted $d = 18\text{nm}$, same as the known value).

(a)

(b)

Fig. 3.3: Device parameter extraction procedure: (a) Step 1 (b) Step 2 until step 5.

Fig. 3.4: Smoothing parameter calibration at V_{off} to achieve smooth transition.

The model smoothing parameters are properly tuned to avoid any ‘glitch’ or ‘spike’ in the first-order derivatives in the C_{gg} . For the surface potential model, there are in total 4 smoothing parameters: ϵ (2.93a), ϵ_I (2.97b), ρ (2.97a) and α (2.94a). The model assumes same default values (5×10^{-3}) for ϵ , ϵ_I and α . The fine tuning needed for ϵ and ϵ_I are shown in Figure 3.4. A higher value of ϵ and ϵ_I will result in glitch in the near- V_{off} region and moderate-inversion, respectively. The strong-inversion smoothing parameter α was kept fixed at default value without any further tuning. The default value of ρ is 0.026 (v_{th}), which was fine-tuned to avoid any glitch with final fitted value of 0.020. The first-order derivative is shown in the inset of Figure 3.4 with the final fitted values with no glitch.

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Finally, the charge model was validated with TCAD for $L_g=2\ \mu\text{m}$ and $L_{gs}=L_{gd}=0.1\ \mu\text{m}$. The C_{gg} vs V_{gs} plot for linear and saturation region are shown in Figure 3.5 (a). The 9 different capacitance components variations with V_{ds} for $V_{gs}=0\text{V}$ is shown in Figure 3.5 (b) with good match. In total, there are four model parameters and four smoothing parameters for the charge model which are listed in Table III.

TABLE III
EXTRACTED MODEL PARAMETERS FROM CHARGE MODEL

MODEL	SYMBOL	TCAD	EXTRACTED
<i>AlGaIn thickness</i>	d (nm)	18	18
<i>Effective GaN doping concentration</i>	N_A (cm^{-3})	10^{15}	0.989×10^{15}
<i>Lowest sub-band parameter</i>	γ_0 ($\text{V} \cdot \text{cm}^{4/3}$)	N.A	3.7×10^{-10}
<i>Second sub-band parameter</i>	γ_1 ($\text{V} \cdot \text{cm}^{4/3}$)	N.A	4.45×10^{-10}
<i>Active region smoothing parameter</i>	ε (V^2)	N.A	1.5×10^{-3}
<i>Active-subthreshold smoothing parameter1</i>	ε_1 (V^2)	N.A	5×10^{-3}
<i>Strong Inversion smoothing parameter</i>	α (N.A)	N.A	5×10^{-3}
<i>Active-subthreshold smoothing parameter2</i>	ρ (V)	N.A	0.020

Fig. 3.5: Charge model validation for $L_g=2\mu\text{m}$ and short access region length (a) C_{gg} vs. V_{gs} for linear and saturation region (b) C_{ij} vs. V_{ds} for $V_{gs}=0\text{V}$.

3.3. HEMT current model extraction

The HEMT drain current model has been developed with the essential physical effects, such as the triangular well approximation and the SCEs, which are built-in the surface potential formulation. Further, the lateral-field effects such as lateral-field mobility degradation and channel-length modulation are modeled through velocity saturation and effective Early voltage, respectively. All these effects are included in the modular form and, thus, can be turned off individually. This section discusses the model calibration for HEMT devices starting from a long channel device and approaching the minimum gate-length device with extraction of related parameters.

As shown in the previous section, the physical parameters, such as d , N_A , γ_0 and γ_l parameters, and unified regional smoothing parameters, are properly calibrated in the long-channel charge model. For the drain current calibration procedure, it begins with the extreme geometry conditions, long channel device but minimum source/drain access region to model the core channel first. Some of the parameters are first set to the default values: $\zeta_n = 0.5$ and $\zeta_b = 1$ (in E_{eff}), $v_{\text{sat}} = 1 \times 10^7$ cm/s, and $\delta_s = 0.005$ (in $V_{\text{ds,eff}}$), $\delta_L = 0.01$ (lateral mobility degradation).

Step 1: At $W_{\infty}/L_{g,\infty}/L_{\text{gs,min}}/L_{\text{gd,min}}$: Measure I_{ds} vs. V_{gs} data at $V_{\text{ds}} = V_{\text{d0}}$ (linear region, $V_{\text{d0}} = 0.05$ V). Fit the drain current equation in the strong inversion region, where transverse field mobility parameters (μ_1, μ_2, μ_3, ν) are tuned to match the data. The effect of the step-1 extraction is illustrated in Figure 3.6.

Fig. 3.6: Model calibration for transverse field mobility parameters as stated in step 1 (μ_1, μ_2, μ_3, v).

Step 2: At $W_\infty/L_{g,\infty}/L_{gs,\infty}/L_{gd,\infty}$: Measure I_{ds} vs. V_{gs} data, at $V_{ds} = V_{d0}$. Fit the drain current equation in the linear region for R_s and R_d extraction. The series resistance model for the access regions is repeated here for convenience

$$R_c = \frac{L_{gc}}{qW\mu_{rc}\sigma} \left(1 + \xi_{rc} \left(\frac{\mu_{rc}(V_{ci} - V_c)}{v_{satc}L_{gc}} \right)^2 \right)^{\frac{1}{2}} \dots \quad c = s/d \quad (3.2)$$

Now as evident, for $L_{gc,\infty}$ ($c=s/d$), R_c depends mainly on μ_{rc} and σ . While for $L_{gc,min}$, R_c depends mainly on σ . It must be noted that the effect of μ_{rc} ($c=s/d$) is different based on the source (saturation region) or drain side (linear region). Thus for step 2 extraction, only μ_{rd} and σ are extracted based on the linear region measurement data as shown in Figure 3.7(a).

Step 3: At $W_\infty/L_{g,\infty}/L_{gs,\infty}/L_{gd,\infty}$: Measure I_{ds} vs. V_{ds} data at $V_{gs} = V_{gg}$ (0.5V). Fit the drain current equation in saturation to extract μ_{rs} and σ as shown in Figure 3.7(b).

Fig. 3.7: Extraction of source/drain resistance for long access region as stated in (a) step 2 to (b) step 3.

Step 4: At $W_{\infty}/L_{g,\infty}/L_{gs,\infty}/L_{gd,min}$: Measure I_{ds} vs. V_{gs} data, at $V_{ds} = V_{d0}$. Fit the drain current equation in the linear region for σ extraction as shown in Figure 3.8.

Step 5: At $W_{\infty}/L_{g,\infty}/L_{gs,min}/L_{gd,\infty}$: Measure I_{ds} vs. V_{ds} data at $V_{gs} = V_{gg}$ (0.5V). Fit the drain current equation in saturation to further retune σ as shown in Figure

Fig. 3.8: Extraction of σ and μ_{rd} with L_{gd} scaling as stated in step 4.

3.9(a). Also to validate, measure I_{ds} vs. V_{gs} data, at $V_{ds} = V_{d0}$ and do model playback to check if any further retuning is necessary as shown in Figure 3.9(b).

Step 2 to step 5 will require iteration to get a good match in both linear and saturation regions along with L_{gc} scalability as the polarization charge term σ is present in all the cases. This extraction procedure is not as simple as in CMOS device, as the access region on both source and drain side adds to the complexity of the model extraction procedure. It is to be noted that velocity saturation term v_{satc} ($c=s/d$) in (3.2) does not have significant effect till now as $L_{g,\infty}$ is considered.

Model Validation: With extraction of μ_{rs} , μ_{rd} and σ along with L_{gd}/L_{gs} scalability, the above model is played-back and validated with TCAD with different L_{gd}/L_{gs} combination as shown in Figure 3.10 (a) and (b) and a good fit in both linear and saturation region is obtained.

(a)

(b)

Fig. 3.9: Extraction of σ and μ_{rs} with L_{gs} scaling as stated in step 5.

Fig. 3.10: Model validation of the source/drain access region resistance for long channel case with $L_{gs}=1\mu\text{m}$ and $L_{gd}=2\mu\text{m}$ (a) I_{ds} - V_{gs} and g_m - V_{gs} at $V_{ds}=0.05\text{V}$ (b) I_{ds} - V_{ds} for different V_{gs} .

Fig. 3.11: Series resistance extraction at shortest channel length as stated in step 6.

Step 6: At $W_{\infty}/L_{g,\min}$: Measure I_{ds} vs. V_{gs} data, at $V_{ds} = V_{d0}$. Fit the drain current equation in the linear region for intrinsic channel resistance r_{ic} extraction as shown in Figure 3.11.

Step 7: At $W_{\infty}/L_{g,\min}$: Measure I_{ds} vs. V_{gs} data, at $V_{ds} = V_{dd}$. Fit the threshold voltage and the subthreshold slope with η_{sc} , α_{dibl} and γ_{sc} as shown in Figure 3.12. It is to be noted that η_{sc} and α_{dibl} are used to tune the threshold voltage shift while γ_{sc} is used to tune the subthreshold slope at higher V_{ds} .

Step 8: At $W_{\infty}/L_{g,\min}$: Measure I_{ds} vs. V_{ds} data at $V_{gs} = V_{gg}$. Now at this point, it is understood that for short channel devices, v_{sat} as well as source/drain saturation voltage v_{satc} ($c=s/d$) will affect the I_{ds} . It will be very complicated to extract three velocity saturation parameters for short channel devices at the same time. In a model, all of these parameters are essentially effective values, which need to be extracted from the measurement data. Thus for this extraction

Fig. 3.12: Short channel threshold voltage and subthreshold swing parameter extraction at shortest channel length as stated in step 7.

procedure, we fit the drain current equation in the saturation region to extract v_{sat} , v_{sats} as R_s will affect the saturation region to large extent. The channel length modulation (ξ_C) and lateral field degradation parameters (δ_L) are extracted to fit the non-zero slope of the I_{ds} - V_{ds} at higher drain voltage. Again v_{satd} is tuned to fit the linear region as R_d is dominant in this region. Next, with fixed v_{sats} and v_{satd} , a length dependent v_{sat} is extracted from I_{ds} vs. V_{ds} for different L_g . A length-dependent v_{sat} model is proposed as

$$v_{sat} = v_{sat1} + \frac{v_{sat2} - v_{sat1}}{1 + \left(\frac{L_g}{v_\alpha} \right)^{v_\beta}} \quad (3.3)$$

Figure 3.13 shows the extracted v_{sat} vs. L_g fitted with the above model. It is noted that the v_{sat} is an extracted parameter which is largely dependent on the extracted v_{sats} of the source side access region. Based on the above model, for

Fig. 3.13: Model fitting of extracted v_{sat} (3.3) using L_g dependency (Step 8).

length scaling, v_{sats} and v_{satd} does not need to be retuned as the length dependency is built-in the v_{sat} parameter.

Step 9: At $W_{\infty}/L_{g,min}$: Measure r_{out} vs. V_{ds} data at $V_{gs} = V_{gg}$. For each gate length, δ_s is tuned to fit the level of output resistance. A length-dependent δ_s model is proposed as

$$\delta_s = \delta_{s1} + \frac{\delta_{s2} - \delta_{s1}}{1 + \left(\frac{L_g}{\delta_{s3}} \right)^{\delta_{s4}}} \quad (3.4)$$

Figure 3.14(a) shows the comparison of length-dependent δ_s and single δ_s in r_{out} of a single technology. Figure 3.14(b) shows the model match using (3.4) and extracted δ_s of the corresponding gate lengths. With this, the length dependent drain current model calibration is completed.

Fig. 3.14 (a) Extraction of L_g dependent δ_s from output resistance (b) Model fitting (3.4) using the geometry dependent δ_s .

3.4. HEMT current model validation

The extracted values used in the drain-current model for GaN HEMT to generate the data for validation are shown in Table IV. It is shown that the total number of parameters needed for the drain current model is 33 for the whole technology. It is noted that the thermal resistance R_{th} is not considered in the TCAD simulation for simplicity. The long channel model with $L_g=10\ \mu\text{m}$ is previously shown in Figure 3.10. The model is played back and compared with TCAD data for the whole technology with gate lengths $L_g=2, 1, 0.5, 0.25\ \mu\text{m}$, as shown in Figure 3.15 to Figure 3.18. As explained in chapter 2, devices with L_g

TABLE IV
EXTRACTED MODEL PARAMETERS FROM CURRENT MODEL

MODEL	SYMBOL	EXTRACTED
<i>Effective transverse field</i>	ζ_n (N.A)	0.5
	ζ_b (N.A)	1
<i>Mobility</i>	μ_1 ($\text{cm}^2.\text{V}^{-1}.\text{s}^{-1}$)	537
	μ_2 ($\text{cm}^{5/3}.\text{V}^{-2/3}.\text{s}^{-1}$)	2.6×10^5
	μ_3 ($\text{V}.\text{s}^{-1}$)	1.7×10^{16}
	ν (N.A)	1.39
<i>Source access region mobility</i>	μ_{rs} ($\text{cm}^2.\text{V}^{-1}.\text{s}^{-1}$)	525
<i>Drain access region mobility</i>	μ_{rd} ($\text{cm}^2.\text{V}^{-1}.\text{s}^{-1}$)	529
<i>Polarization charge density</i>	σ (cm^{-2})	6.78×10^{12}
<i>Intrinsic Series resistance</i>	$r_{is}=r_{id}$ (Ω)	800
<i>Prefactor for quasi-2D solution</i>	η_{sc} (N.A)	15.8152
<i>DIBL parameter</i>	α_{dibl} (N.A)	0.78
<i>Minimum potential parameter</i>	γ_{sc} (N.A)	0.0656
<i>Source velocity saturation</i>	ν_{sats} ($\text{cm}.\text{s}^{-1}$)	1.022×10^7
<i>Drain velocity saturation</i>	ν_{satd} ($\text{cm}.\text{s}^{-1}$)	5.14×10^6

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MODEL	SYMBOL	EXTRACTED
<i>Lengths dependent channel velocity saturation</i>	v_{sat1} (cm.s ⁻¹)	88026.72
	v_{sat2} (cm.s ⁻¹)	9.148983×10^{12}
	v_{α} (cm)	3.152019×10^{-14}
	v_{β} (N.A)	0.4787992
<i>Channel length modulation</i>	ξ_C (N.A)	0.1703
<i>Lateral field mobility degradation</i>	δ_L (N.A)	0.17665
<i>Lengths dependent smoothing function for effective drain-source voltage</i>	δ_{s1} (V)	-0.06546166
	δ_{s2} (V)	2.873555
	δ_{s3} (cm)	0.009915064
	δ_{s4} (N.A)	0.4586443

$>1 \mu\text{m}$ suffer from slight threshold voltage roll-off but not significant subthreshold slope degradation with V_{ds} , as shown in Figs. 3.15 and 3.16. However, devices with $L_g < 0.5 \mu\text{m}$ exhibit severe threshold voltage roll-off as well as subthreshold slope degradation at high V_{ds} , as shown in Figs. 3.17 and 3.18. The proposed model, implemented with correct parameter extraction methodology, is able to capture the SCEs in GaN HEMT devices.

As mentioned in (3.3) and (3.4), geometry dependent v_{sat} and δ_s are used in the model. To validate these two fitting parameters, measurement for a different channel length ($L_g = 0.35 \mu\text{m}$, not used for model extraction) is used and compared with the model playback as shown in Figures 3.13 and 3.14(b). The model playback is shown for I_{ds} - V_{gs} and I_{ds} - V_{ds} in Figure 3.19 and g_m - V_{gs} and g_{ds} - V_{ds} in Figure 3.20 with satisfactory matching. The modeled data match well with all TCAD data. Therefore, it can be concluded that the model is physical and able to scale for different geometries and voltages.

Fig. 3.15: Validation by model play-back and prediction for (a) I_{ds} vs. V_{gs} for different V_{ds} , (b) I_{ds} vs. V_{ds} for different V_{gs} , $L_g=2\mu\text{m}$, $L_{gs}=1\mu\text{m}$, $L_{gd}=2\mu\text{m}$.

Fig. 3.16: Validation by model play-back and prediction for (a) I_{ds} vs. V_{gs} for different V_{ds} , (b) I_{ds} vs. V_{ds} for different V_{gs} , $L_g=1\mu m$, $L_{gs}=1\mu m$, $L_{gd}=2\mu m$.

Fig. 3.17: Validation by model play-back and prediction for (a) I_{ds} vs. V_{gs} for different V_{ds} , (b) I_{ds} vs. V_{ds} for different V_{gs} , $L_g = 0.5 \mu\text{m}$, $L_{gs} = 1 \mu\text{m}$, $L_{gd} = 2 \mu\text{m}$.

Fig. 3.18: Validation by model play-back and prediction for (a) I_{ds} vs. V_{gs} for different V_{ds} , (b) I_{ds} vs. V_{ds} for different V_{gs} , $L_g=0.25\mu\text{m}$, $L_{gs}=1\mu\text{m}$, $L_{gd}=2\mu\text{m}$.

Fig. 3.19: Validation of L_g dependent v_{sat} and δ_s model from (3.3) and (3.4) by model play-back and prediction for (a) I_{ds} vs. V_{gs} for different V_{ds} , (b) I_{ds} vs. V_{ds} for different V_{gs} , $L_g=0.35\mu\text{m}$, $L_{gs}=1\mu\text{m}$, $L_{gd}=2\mu\text{m}$.

Fig. 3.20: Validation of L_g dependent v_{sat} and δ_s model [Lines] from (3.3) and (3.4) by model play-back and prediction compared with TCAD [Symbols] for (a) g_m vs. V_{gs} for different V_{ds} , (b) g_{ds} vs. V_{ds} for different V_{gs} , $L_g=0.35 \mu m$, $L_{gs}=1 \mu m$, $L_{gd}=2 \mu m$

3.5. Conclusion

The HEMT model extraction procedure is done systematically due to mostly uncorrelated model parameters. The physical parameters such as d , N_A , γ_0 and γ_l are able to be extracted from depletion, moderate- and strong-inversion of the C_{gg} capacitance data at long channel. The model smoothing parameters (ε , ε_l , ρ and α) are optimized from the derivatives of C_{gg} condition. The mobility models (μ_1 , μ_2 , μ_3 , ν) are extracted from long-channel I_{ds} vs. V_{gs} at linear condition. Currently, the fabricated GaN HEMTs are 3-terminal devices without any body contact, thus the transverse field parameters (ζ_n , ζ_b) are kept at default values without any body-bias effect. Next, the source/drain access region parameters (μ_{rs} , μ_{rd} , and σ) are extracted for different L_{gs}/L_{gd} combinations for long channel case. The series resistances (r_{is} , r_{id}) are to be extracted from the short-channel I_{ds} vs. V_{gs} in linear region. From short-channel I_{ds} vs. V_{ds} at $V_{gs}=V_{gg}$, ν_{satd} , ν_{sats} and ν_{sat} can be optimized to match the linear and saturation regions. At each gate length in a single technology, ν_{sat} and δ_s parameters can be extracted from the I_{ds} vs. V_{ds} and r_{out} vs. V_{ds} at $V_{gs}=V_{gg}$, respectively after which these data can be fitted with empirical functions (3.3) and (3.4). The channel length modulation (ζ_c) and lateral field degradation parameters (δ_L) can be extracted from the saturation region slope of I_{ds} vs. V_{ds} at $V_{gs}=V_{gg}$. The short-channel threshold voltage and subthreshold slope parameters (η_{sc} , α_{dibl} and γ_{sc}) can be extracted from the short channel $\log(I_{ds})$ vs. V_{gs} at $V_d=V_{d0}$ and $V_d=V_{dd}$. The above model extraction procedure presents a simplistic approach towards calibration of GaN HEMT devices followed by model playback with good match with measurement data.

Chapter 4: Trapping and De-trapping in GaN HEMTs

4.1. Trapping/detrapping phenomena in GaN HEMTs

AlGaIn/GaN based HEMTs represent a very promising device for application in the radar and communication fields, and for power conversion systems. However, one of the most critical issues for AlGaIn/GaN HEMTs is the so-called “*current collapse*” [12, 13]: the presence of traps—located either under the gate or in the gate–drain access region—which results in a recoverable decrease in drain current when exposed to high negative gate voltages (gate-lag), or to high drain voltage levels (drain-lag) in OFF-state. The existence of these dispersion effects observed in GaN based devices has limited the initial expectations. The DC characteristics no longer represents the high-frequency operation because of the electron capture at the surface, bulk, and interface traps [74]. Various forms of trapping effects have been reported, such as transconductance frequency dispersion [68-70], current collapse [78], [79] and gate- and drain-lag transients [31]. Current collapse has been explained by

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the concept of virtual gate [80], associated with additional charge trapping at the AlGaIn/GaN interface or in the GaN bulk region of the transistor. Apart from current collapse, “*device degradation*” is another serious event that occurs due to lattice defects by excessive mechanical stress caused by converse piezoelectric effect in the regions with high electric fields. These defects act as traps that cause current to degrade with time.

Current collapse and device degradation have similar impact on the I - V characteristics, both reducing the current flowing through the channel, especially in the knee region of the I - V plane. The main difference is that the current collapse is reversible and the degradation is not. The difference in the mechanism is that current collapse is caused by trapping of electrons in existing traps while device degradation is caused by creating new defects, and hence, new traps in the device, on which charge is permanently trapped. In this chapter, we aim to characterize and model the current collapse phenomenon. In GaN HEMTs, traps can affect the device I - V characteristics by

- a. Directly trapping electrons that would otherwise be part of the mobile channel electrons, i.e., depleting the 2DEG density in the channel.
- b. Trapping charges elsewhere, (not in the channel), thereby creating a potential barrier that impedes the flow of channel electrons.

Most of the current research focuses on different ways to locate and characterize the traps, such as pulsed I_{ds} - V_{ds} measurements, and current deep-level transient spectroscopy [81]. Primarily based on their location, traps in GaN HEMTs can be divided into 4 types, as shown in Fig. 4.1, such as surface states (T1), barrier traps (T2), interface traps (T3), and buffer/substrate traps

Fig. 4.1: HEMT cross-section showing possible locations of traps: Trap T1 is at the SiN-passivation/AlGaN interface, T2 in the AlGaN barrier, T3 at the AlGaN/GaN interface, and T4 in the deep GaN buffer [87].

(T4). Zhang *et. al.* [82] studied the effects of AlGaN/GaN interface acceptor-like traps (T3) on the transient responses of GaN HEMTs. The possible mechanisms of gate-lag in GaN HEMTs were reported in [67, 76], attributing it to the surface and barrier traps (T1 and T2). On the contrary, drain-lag effects were attributed mostly to buffer or substrate traps (T4) [77, 78]. However, very few reports actually focus on compact modeling of trapping/detrapping effects on the drain current in GaN HEMTs. The existing CM's [86] for GaN HEMTs do not consider the effects of trapping/detrapping on the DC as well as pulsed I - V characteristics. Thus, developing a compact drain-current model incorporating the effect of trapping/detrapping phenomena is highly necessary for the design of high-frequency (HF) circuits as well as design for reliability, which has been the motivation behind this work [87].

TABLE V
TRAP CHARGE MODELING

Traps in the GaN HEMT			
Interface Traps, T3		Surface, Barrier & Bulk Traps (T1, T2, T4)	
Under the Gate: DC I_{ds}-V_{ds} (Saturation)	Extrinsic L_{gd}: DC I_{ds}-V_{ds} (Linear)	Under the Gate, Pulsed I_{ds}-V_{ds}: Gate Lag	Extrinsic L_{gd}, Pulsed I_{ds}-V_{ds}: Gate/Drain Lag

This work presented in this chapter focus on modeling the DC I - V and pulsed I - V characteristics by considering interface traps and bulk/surface traps separately. It was assumed that type T3 traps will mostly affect the DC I - V as these traps are in direct interaction with the 2DEG. However, trapping at the surface, barrier, or buffer traps are considered under gate-lag and both gate- and drain-lag conditions, the effect of which should be observed in pulsed measurements when the device is subjected to stress for a finite time T_{off} . The assumption is reasonable since it is unlikely that the 2DEG will cross the heterostructure barrier, reach the surface states, or go deep in the buffer under normal DC operating conditions. Based on their location, the effect of traps on both the DC and pulsed I - V characteristics varies. Traps under the gate mostly result in threshold-voltage shifts (ΔV_{off}) affecting the saturation region of the I_{ds} - V_{ds} curve. Trapping in the drain access region (L_{gd}) affects the linear region of the I_{ds} - V_{ds} curve, resulting in dynamic on-resistance (dyn- $R_{DS,ON}$) degradation. Thus, for both DC and pulsed I - V models, traps are considered under the gate and in the extrinsic drain access region separately, as shown in Table V. The extracted model parameters obtained from trapping in the drain access region are then applied for the source access region to develop the full model. Apart from DC and pulsed I - V characteristics, a generic model must also

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be able to simulate the transient response of the devices under stress conditions. Based on the first-order differential equation for the threshold-voltage shift, a compact model is proposed, that accurately simulates drain-current transient of the HEMT device under gate-lag conditions.

4.2. DC trap modeling

In the recent years with scaling of insulators, there has been considerable interest in studying the effects of oxide-silicon interface traps on the DC performance of nanoscale FET devices [88]–[92]. Similar to the MOS system, traps at the 2DEG interface should also play a significant role in threshold voltage shift and reduction of drain current in GaN HEMTs [93], [94]. The following section presents a compact DC model which is an extension of the current model presented in chapter 2, with the incorporation of the interface trap density in the charge-voltage equation.

4.2.1. Model formulation

For this model formulation, acceptor-like traps are considered at the 2DEG interface with trap density N_t (cm^{-2}). An acceptor-like trap can either be negative (ionized) with charge states of -1 or neutral like an acceptor with charge state of zero. To model the effects of trap in the saturation and linear region of the I_d - V_{ds} characteristics, traps are considered separately under the gate and in the drain access region respectively. Considering traps under the gate, the effective electron trap charge density (Q_{nT}) can be expressed as [94]

$$Q_{nT} = qN_t \times \frac{c_{ns}n + e_{ps}}{c_{ns}n + e_{ns} + c_{ps}p + e_{ps}} \quad (4.1)$$

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$$C_{\text{ns}} = v_n \sigma_n \quad (4.1a)$$

$$C_{\text{ps}} = v_p \sigma_p \quad (4.1b)$$

where σ_n (σ_p) is the capture cross-section for electron (holes), v_n (v_p) is the thermal velocity of electrons (holes), e_{ns} (e_{ps}) is the electron (hole) emission rates, and n (p) is the electron (hole) concentration in cm^{-3} . For acceptor-like traps, the electron and hole emission rates are given by

$$e_{\text{ns}} = v_n \sigma_n n_i e^{E_T/v_{\text{th}}} \quad (4.2a)$$

$$e_{\text{ps}} = v_p \sigma_p n_i e^{-E_T/v_{\text{th}}} \quad (4.2b)$$

where E_T is the interface-trap energy level referenced to the intrinsic Fermi level E_i . Following the analysis in our base model [3], 2DEG density n_s was related to the gate (V_g) and channel (V_c) voltages through Gauss' law as

$$n_s = \frac{C_d}{q} (V_g - V_{\text{off}} - V_c - E_f) \quad (4.3)$$

where the Fermi potential, E_f in eV, is referenced to the bottom of the triangular quantum well (conduction-band edge), channel voltage $V_c = V_s$ or V_d at the source or drain ends ($y = 0$ or L_g), respectively, C_d is an effective capacitance (per unit area) between the gate and 2DEG, and V_{off} is the threshold voltage. A single-piece explicit E_f expression that is valid from subthreshold to strong inversion can be obtained as given by

$$E_f(V_c) = V_g - V_{\text{off}} - \Delta E_f \quad (4.4)$$

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where ΔE_f is defined in chapter 2, equation (2.36). Once E_f is calculated from (4.4), the electron concentration (n) must be obtained to calculate (4.1). For degenerate semiconductors, a commonly used expression for Fermi integral is given by [95]

$$n(V_c) = N_c \left[e^{-E_f(V_c)/v_{th}} + 0.27 \right] \quad (4.5)$$

where N_c is conduction band density of states. Using (4.5) in (4.1), Q_{nT} can be obtained explicitly. The final E_f solution is then obtained iteratively by replacing V_{off} in (4.4) with $(V_{off} + Q_{nT}/C_d)$ in each iteration steps. Once a trap dependent E_f model is developed, a compact surface-potential (ϕ_s) model, referenced to the Fermi level in the body where the channel voltage $V_c = V_s$ or V_d at the source or drain ends ($y = 0$ or L_g) respectively, can be expressed as

$$\phi_s(V_c) = V_c + E_f(V_c) \quad (4.6)$$

As the electron concentration $n(V_c)$ changes along the channel, Q_{nT} changes with V_{ds} . Considering an average of the total Q_{nT} from source and drain and adapting the ϕ_s model to the current model (presented in chapter 2), the final drain current can be expressed as [3]

$$I_{ds} = W \mu C_d / L_{eff} \left(\frac{V_g - V_{off} - \overline{Q_{nT}} / C_d}{-\frac{\phi_{s,eff} + \phi_{d,eff}}{2} + 2v_{th}} \right) V_{ds,eff} \quad (4.7)$$

$$\overline{Q_{nT}} = 0.5(Q_{nT,seff} + Q_{nT,deff}) \quad (4.7a)$$

where $Q_{nT,seff}$ ($Q_{nT,deff}$) is the effective electron trap charge density at the source (drain) end, $\phi_{c,eff} \equiv \phi_s(V_{c,eff})$ with $c = s/d$ for source/drain (S/D). Detailed

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expressions for the effective drain-source voltage ($V_{ds,eff}$) and mobility (μ) are presented in chapter 2.

The interface traps also affect the S/D access resistance (R_s/R_d). The ungated access resistances are modeled using a sub-circuit approach, in which the internal node voltages (V_{ci}) are calculated by the SPICE simulator, and $R_c = R_s/R_d$, with $c = s/d$ for S/D, respectively, is given by equation (2.74) in chapter 2:

$$R_c = \frac{L_{gc}}{qW\mu_{rc}n_s} \sqrt{1 + \xi_{rc} \left(\frac{\mu_{rc}(V_c - V_{ci})}{v_{satc}L_{gc}} \right)^2} \quad (4.8)$$

where μ_{rc} and v_{satc} ($c=s/d$) are the mobility and saturation velocity in the S/D access region of length $L_{gc} = L_{gs}/L_{gd}$, n_s is the 2DEG density, and ξ_{rc} is a fitting parameter.

In the absence of gate modulation, the available 2DEG density n_s is equal to the polarization charge σ as it is in the source/drain access region. To capture the effect of trap density N_t in the drain access region, the effective 2DEG density in (4.8) is then given by $n_s = (\sigma - N_t)$. The effect of interface trap dependent R_d on the drain current and transconductance g_m was simulated in TCAD and shown in Fig. 4.2 considering 3 cases as described below:

- Curve A : Long L_g ($10\mu m$) and short L_{gd} ($0.1\mu m$) with negligible R_d
- Curve B : Long L_{gd} ($5\mu m$) with high R_d but no traps in the extrinsic drain region
- Curve C : Long L_{gd} and traps in the full interface

A fixed value of $\sigma = 6.8 \times 10^{12} \text{ cm}^{-2}$ was used in the simulation and the model.

After calibrating the core model with curve A, (4.8) was used to model curve B

Fig. 4.2: Long channel HEMT ($L_g=10\ \mu\text{m}$): Modeled (lines) $I_{ds}-V_{gs}$ and g_m-V_{gs} characteristics compared with the TCAD data (symbols); Curve A: Short L_{gd} to model interface traps under the gate (core trap model). Curve B: Long L_{gd} with traps only under the gate to model the trap free drain access resistance. Curve C: Long L_{gd} with traps in the whole interface to develop the complete trap model.

with accurate extraction of μ_{rd} and v_{satd} . For curve C, the effective 2DEG $= (\sigma - N_t)$ was considered instead of σ . Clearly curve C results in a reduced drain current where the effective 2DEG in the drain access region is less. The model shows a good match with simulation results.

To validate the E_f solution, AlGaIn/GaN HEMT (barrier thickness=18nm) with interface acceptor-like traps was simulated using TCAD. Fig. 4.3 shows the unified E_f model (lines) versus gate bias, compared with the exact coupled P-S solution (symbols), and model scaling with interface trap densities. The differences (or absolute errors) between the unified model and the coupled solution are shown in the inset for different trap densities, showing an overall error below $\sim 4\ \text{mV}$. The developed model is found to be scalable over all major device parameters with errors in the millivolt range, due to its

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analytical nature, capturing user-defined trap density as input parameter for obtaining unified surface potential solution. To verify the current model with interface traps only under the gate, simulations were done with long channel length ($L_g=10\mu\text{m}$) and very short source/drain access region length ($L_{gs}/L_{gd}=0.1\mu\text{m}$) to nullify the effects of access resistance. Fig. 4.4 shows the I_{ds} - V_{gs} curve for different interface trap density at a low drain voltage of $V_{ds}=0.01\text{V}$. A clear threshold voltage shift is observed for different N_t , nicely captured by the above model. The complete I_{ds} - V_{gs} curve for fixed $N_t=7.5\times 10^{11}\text{ cm}^{-2}$ at different V_{ds} is shown in Fig. 4.5. Subsequently, to validate the full interface trap charge model, $N_t=7.5\times 10^{11}\text{ cm}^{-2}$ was considered under the gate as well as in the extrinsic source/drain access region. L_g , L_{gs} and L_{gd} were all fixed to $2\mu\text{m}$ so that the trap dependency on R_s and R_d can be validated. The model is able to capture the I_{ds} and g_m characteristics as shown in Fig. 4.6.

Fig. 4.3: Unified E_f solutions [solid line] versus V_{gs} compared with the coupled Poisson-Schrödinger solutions from TCAD [symbols] for different interface trap density. Inset: model error with respect to the P-S solution.

Fig. 4.4: Simulated pulsed $I_{ds} - V_{gs}$ characteristics (symbol) of HEMT (with long L_g and short L_{gd} and L_{gs}), fitted with the model (solid line) for a wide range of intrinsic trap density.

Fig. 4.5: Simulated pulsed $I_{ds} - V_{gs}$ characteristics (symbol) of HEMT, fitted with the model (solid line) for different V_{ds} . The trap density is fixed at $7.5 \times 10^{11} \text{ cm}^{-2}$.

(a)

(b)

Fig. 4.6: (a) Modeled (lines) I_{ds} - V_{gs} characteristics and (b) I_{ds} - V_{ds} characteristics compared with the TCAD data (symbols) for HEMT with $L_g = L_{gs} = L_{gd} = 2 \mu\text{m}$. The trap density is fixed at $7.5 \times 10^{11} \text{ cm}^{-2}$.

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One of the serious reliability concern in HEMT devices is the “kink effect”, whereby the drain current shows a sudden increase even at low drain bias [88, 89]. The kink effect, also known as soft breakdown, is a very common feature of the I - V characteristics in AlGaAs/InGaAs/GaAs and InAlAs/InGaAs/InP HEMTs. Recently, a few reports show the existence of kink effect in GaN HEMTs [98]–[101]. The main underlying mechanisms are attributed to impact ionization effects that point to a direct correlation with anomalous conduction aspects such as the kink in the output current and the bell-shaped curve of the gate leakage current, especially in InP-based structures. However, impact ionization effects does not seems to be the main mechanism in GaN HEMTs as reported by [88] whereby a direct correlation of increase in drain current with the gate current due to the impact ionization-generated holes was not observed. For GaN based HEMT devices, kink effect has been attributed to trap-assisted phenomena which is more significant in the drain side of the device due to the high electric field.

The model presented in the previous section can be tuned to capture the kink effects. Recalling (4.7a), the drain current term can be re-expressed as

$$I_{ds} = W \mu C_d / L_{eff} \left(\frac{V_g - V_{off} - (\alpha_{Ts} Q_{nT,seff} + \alpha_{Td} Q_{nT,deff}) / C_d}{-\frac{\phi_{s,eff} + \phi_{d,eff}}{2} + 2v_{th}} \right) V_{ds,eff} \quad (4.9)$$

where α_{Ts} and α_{Td} are two fitting parameters to tune the effect of the corresponding traps at the source and drain side, respectively. The ratio of α_{Td} to α_{Ts} is the charge partitioning ratio. By default, $\alpha_{Td} = \alpha_{Ts} = 0.5$ i.e., the charge partitioning scheme is 50/50. However, if α_{Td} is tuned larger than 0.5 with $\alpha_{Ts} = (1 - \alpha_{Td})$, the drain current shows a sudden increase or kink as is shown in Fig.

Fig. 4.7: Model playback with different trap charge partition scheme from $Q_{nT,deff} / Q_{nT,seff} = 50/50$ to $100/0$. Inset: Effect of different activation energy E_A on the DC $I-V$ characteristics.

4.7. Model playbacks with different partition schemes from 50/50 to 100/0 (D/S) are also plotted showing the maximum kink effect for 100/0 scheme. Also shown in the inset is the effect of the activation energy of the traps (E_A , referenced to the bottom of conduction band) on the position of the kink voltage V_{kink} . With increasing E_A , the V_{kink} increases. This can be understood from the band diagram. With deeper traps in the band-gap (higher E_A), a higher electric field is necessary to detrapp the electrons from the trap centers, thus resulting in a higher value of V_{kink} . Measured $I_{ds}-V_{ds}$ of AlGaIn/GaN HEMT on Si-substrate from different vendor exhibiting kink effect was fitted with the model (partition scheme: 80/20) and is shown in Fig. 4.8 (a). The output resistance r_{out} vs. V_{ds} shown in Fig. 4.8(b) also validates the above kink effect model.

Fig. 4.8: (a) Modeled (lines) I_{ds} – V_{ds} characteristics and (b) r_{out} – V_{ds} characteristics compared with measured data (symbols) for HEMT with $L_g = 0.25 \mu\text{m}$ exhibiting kink effect. Partition scheme of (80/20) was used to fit the model.

4.2.2. Interface state density from conductance method

The previous section focused on modeling the effects of interface traps on the DC characteristics, provided the trap density N_t is known. Thus, an accurate and simpler method must be used to extract N_t which, in turn, would be used as an input parameter for the DC trap model. In 1967, Nicollian and Goetzberger proposed one of the most sensitive methods to evaluate the interface-trap density per unit energy D_{it} , popularly known as the conductance method [102]. This method can be used to measure the interface-trap densities of the order of $10^9 \text{ cm}^{-2}\text{eV}^{-1}$ and even lower. The conductance method can extract D_{it} in both the depletion and weak inversion portion of the bandgap. This method is based on measuring the equivalent parallel conductance G_P of an MOS capacitor as a function of bias voltage and frequency. This conductance represents the loss mechanism caused by capture and emission of carriers by the interface traps, and can be used to extract the interface trap density. In this study, AlGaIn/GaN diode capacitor is represented with equivalent circuit models as shown in Fig. 4.9(a), where C_d is the barrier capacitance per unit area, C_s is the GaN capacitance per unit area, R_{it} and C_{it} are the resistance and capacitance components per unit area related to interface traps, and G_t is tunnel conductance per unit area related to leakage current. The measurement circuit is shown in Fig. 4.9(b), where C_m and G_m represent the measured capacitance and conductance per unit area, respectively. The equivalent parallel circuit is shown in Fig. 4.9(c), where C_P and G_P represent the equivalent parallel capacitance and conductance per unit area respectively and are given by [103]–[105]:

Fig. 4.9: Equivalent circuit for conductance method: (a) AlGaIn/GaN heterostructure capacitor with interface trap time constant $\tau_{it} = C_{it}R_{it}$ (b) the measured circuit (c) simplified circuit of (a). [102]

$$C_p = C_s + \frac{qD_{it}}{1 + (\omega\tau_{it})^2} \quad (4.10)$$

$$\frac{G_p}{\omega} = \frac{q\omega\tau_{it}D_{it}}{1 + (\omega\tau_{it})^2} \quad (4.11)$$

where $C_{it} = q \cdot D_{it}$, ω is the radial frequency and $\tau_{it} = C_{it} \cdot R_{it}$ is the interface trap time constant. Eq. (4.11) becomes symmetrical in $\omega \cdot \tau_{it}$ as G_p is divided by ω . These two equations are for interface traps with a single trap energy (STE) level in the band gap. However, interface traps normally are continuously distributed as reported in [106]–[108]. With multiple trap energy (MTE) function, these two equations are rewritten as [109], [110]

$$C_p = C_s + \frac{qD_{it}}{\omega\tau_{it}} \tan^{-1}(\omega\tau_{it}) \quad (4.12)$$

$$\frac{G_p}{\omega} = \frac{qD_{it}}{2\omega\tau_{it}} \ln[1 + (\omega\tau_{it})^2] \quad (4.13)$$

The conductance method has been a preferred choice over other methods because for (4.11) and (4.13), there is no semiconductor capacitance

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C_S in the equations. In equation (4.11), at $\omega=1/\tau_{it}$, G_P has a maximum and $D_{it}=2G_P/(q.\omega)$. For equation (4.13), when G_P the maximum, $\omega=2/\tau_{it}$ and $D_{it}=2.5G_P/(q.\omega)$. Thus, by fitting (4.11) or (4.13) with the measurement data, D_{it} and τ_{it} can be determined from the maximum G_P and ω at the location of the peak conductance. The measured G_P/ω versus ω plot of AlGaIn/GaN 2-terminal diode at $V_g=-2.8V$ is shown in Fig. 4.10(a) and fitted with (4.11) and (4.13). It is seen that MTE model from (4.13) is better fitted with the measurement data as compared to the STE model in (4.11). The spread of the G_P/ω curve is not well captured by (4.11). Also it should be mentioned that measured G_P/ω versus ω curve is slightly broader than the MTE curve calculated from equation (4.13), which may be due to the interface trap time constant dispersion caused by the fluctuation of the surface potential due to non-uniformities in AlGaIn/GaN interface traps as well as GaN buffer doping density.

Using the MTE model, the measured G_P/ω versus ω compared with the model for $V_g = -2.8V$ and $-2.68V$ are plotted in Fig. 4.10(b), and the D_{it} extracted is around 4.8×10^{11} and $9.5 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ respectively. The trap time constants τ_{it} of these devices extracted at $V_g = -2.8V$ and $-2.68V$ are $\sim 1.2 \mu s$ and $0.2 \mu s$, respectively, thus showing an exponential dependence on the gate bias near the depletion region. This indicates the presence of a distribution of trap energy states. These electrically active traps may represent material imperfections such as impurities or point defects, dislocations, etc. that are capable of capturing and emitting charge carriers with a specific time constant. The presence of MTE levels in the interface or in deep buffer can also be studied from the pulsed measurements by stressing the devices in ON-state and will be discussed in the next section.

Fig. 4.10: (a) Measured [symbols] G_p/ω fitted with single trap energy level (4.11) [dashed line] and multi trap energy levels (4.13) [dashed line-cross] model for $V_{gs} = -2.8\text{V}$ (b) Measured [symbols] G_p/ω for $V_{gs} = -2.8\text{V}$ and -2.6V fitted with MTE model (4.13) [dashed line].

4.2.3. Multi-Trap Energy: characterization & modeling

The unintentionally doped GaN buffer and the heterostructure interface in AlGaIn/GaN HEMTs contains various defects or trap states resulting in current collapse and other trapping related reliability issues. It is not surprising to find several trap energy levels instead of a single energy level as evident from the conductance measurement in the previous section. Also, traps from different sources with different energy levels may exist together. By analysing the revival of collapsed current using incident light with varying wavelengths, the probability of the presence of MTE-levels had been reported in [111]. A current collapse model incorporating two distinct trap levels of 1.80eV and 2.85eV based on photoionization spectra was proposed by K. B. Klein *et al.* [112]. However, such photoionization spectral studies are more effective with gateless or semi-transparent gate device structures. In this section, pulsed I-V measurement technique was used to validate the existence of MTE levels.

Current reports on trap characterization focus mainly on fully OFF-state stress conditions which facilitate the study of surface/barrier related trapping that results in $\text{dyn-}R_{\text{DS,ON}}$ degradation and threshold voltage shift. A semi-ON state bias condition resulting in partial depletion of the channel had been adopted earlier to study the buffer related traps [113]. However, the negative bias to the gate electrode may induce some surface and barrier related trapping, resulting in both surface/barrier and buffer related components. On the other hand, under fully ON-state stress with high drain voltage, the channel electrons can spill over and gain enough energy at the gate edge of the drain side to reach deep into the GaN buffer. The high drain voltage may activate the otherwise deep trap levels in the energy bandgap resulting in electron capture process.

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ON-state stress can also be divided into long-hour and short-duration stress; the former results in the generation of interface traps and surface related traps due to hot electron effects, the physical origins of the traps yet have not been distinctly established. J. A. del Alamo *et. al.* [80], [114] have reported the absence of a hot-electron based degradation signature during their long-time stress tests and attributed “*inverse piezoelectric effects*” as a possible degradation mode. However, under short period ON-state stress condition, W. D. Hu *et. al.* [115], [116] have reported a hot-electron buffer trapping effect. Thus a short-time ON-state stress condition was found to be a more relevant condition for the study of DC trapping mechanism.

The device dimensions used for this study are $L_{gs}=2\ \mu\text{m}$, $L_g=2\ \mu\text{m}$, gate $W_g=80\ \mu\text{m}$ and $L_{gd}=6\ \mu\text{m}$ with a threshold voltage of -2.5V . Temperature dependent I_{ds} transient measurements from 40°C to 120°C under different ON-state drain quiescent bias (V_{dq}) conditions were performed using Agilent B1505A power device analyser. For the measurements, the gate terminal was biased at (V_{gq}) $=0\text{V}$ and the drain terminal was stressed at different voltages (V_{dq}) $=10$ to 60V with a step of 10V as shown in Fig. 4.11. The V_{dq} or the filling pulse was maintained for a period of 1s . These biasing conditions ensure the injection of channel electrons into the various trap levels around the 2DEG. Consecutively, after the 1s filling pulse, the I_{ds} transient signals were measured as a function of time by ramping down the measurement drain voltage (V_{ds}) to 1.5V , while maintaining the measurement gate voltage (V_{gs}) at 0V . To avoid self-heating effects, a low V_{ds} was chosen for measurements.

Fig. 4.11: Representation of transient drain current measurement method under ON-state stress with stress time of 1s for a gate quiescent bias of $V_{gq}=0V$ and drain quiescent bias of V_{dq} varying from 10-60V. (Time & measurement points not to scale)

The activation energies (E_A 's, referenced to the bottom of conduction band) for the electron emission from the trap levels are determined using the Arrhenius analysis of the temperature dependent emission time constants. I_{ds} transient were first fitted using a polynomial function, [117]

$$I_{ds}(x) = a_0 + a_1x + \dots + a_{n-1}x^{n-1} \quad (n = 10, x = \log(\text{time})), \quad (4.14)$$

where a_n represents the coefficients of the $(n-1)^{\text{th}}$ order term. Then, the derivative of the I_{ds} transient was evaluated to obtain the peak that denotes the emission time (τ_E) as shown in Fig. 4.12 (a) and (b) for 40°C and 100°C respectively. It is seen that for 40°C, τ_E increases with increasing stress voltage V_{dq} . However, for a high temperature of 100°C, the emission time starts to saturate at higher V_{dq} . For higher temperature $T=120^\circ\text{C}$, emission time sharply decreases at $V_{dq} > 60V$ as shown in Fig. 4.13(a). Based on the peaks of the differential signals after applying V_{dq} of 10 to 60V with steps of 10V, different traps with activation energies of 0.44eV, 0.51eV, 0.55eV, 0.58eV, 0.64eV and

Fig. 4.12: Differential signals of the temperature-dependent I_{ds} transients obtained from (4.14) under different V_{dq} stress conditions at (a) 40°C and (b) 100°C for GaN HEMT.

0.73eV, and the corresponding capture cross sections of $4 \times 10^{-21} \text{cm}^2$, $2.6 \times 10^{-20} \text{cm}^2$, $8.5 \times 10^{-20} \text{cm}^2$, $3.5 \times 10^{-19} \text{cm}^2$, $2.4 \times 10^{-18} \text{cm}^2$ and $4.2 \times 10^{-17} \text{cm}^2$ respectively, were obtained from the Arrhenius plot [118]. Figure 4.13(b) shows the compiled Arrhenius plots showing the different E_A 's obtained for different V_{dq} conditions and the physical origins of the traps with their corresponding E_A 's are shown in the inset [111-114]. The obtained E_A 's exhibited a linear dependency with the applied- V_{dq} conditions. This behaviour suggested that the obtained E_A 's must be from MTE levels rather than a single discrete trap energy level. A detailed study of trap generation rate dependence at different drain biases was also suggested by Koudymov et. al. [121]. Figure 4.14 shows the extracted τ_E as a function of V_{dq} at different temperatures. At measurement temperatures $\leq 80^\circ \text{C}$, τ_E increases with V_{dq} till $\sim 50 \text{V}$ beyond which it saturates. For temperatures $> 80^\circ \text{C}$, τ_E shows a decreasing trend for higher V_{dq} . This anomalous behavior under the combination of high V_{dq} and high measurement temperature is attributed to self-heating effects in the GaN HEMTs.

Fig. 4.13: (a) Differential signals of the temperature-dependent I_{ds} transients obtained under different V_{dq} stress conditions at 120°C for GaN HEMT with device dimensions: $L_{gs}/L_g/L_{gd}/W_g = 2/2/6/80 \mu\text{m}$. (b) The corresponding Arrhenius plots for determining the activation energies obtained under different V_{dq} stress conditions. Inset: physical origin of the different traps.

Fig. 4.14: Emission time constants τ_E vs. V_{dq} at different measurement temperatures (T) for GaN HEMT with device dimensions: $L_{gs}/L_g/L_{gd}/W_g = 2/2/6/80 \mu\text{m}$. τ_E decreases at higher V_{dq} for $T > 80^\circ\text{C}$.

In order to understand the physics governing the trapping and detrapping mechanisms from MTE levels, 2-D numerical simulation using TCAD was done with the trap information obtained from the measurements. Poisson's equation along with the carrier continuity equations for electrons and holes were solved by taking into consideration the contribution of mobile and fixed charges and ionized traps. The dynamic traps were modelled by a Shockley–Read–Hall recombination term included in the continuity equations. For transient trap simulations, an additional differential-rate-equation was incorporated to account for emission and capture processes. As a stress voltage (filling pulse), gate terminals were biased at 0V (V_{gq}) and a drain bias (V_{dq}) of 10 to 60V was applied for a period of 1s, with a rise/fall time of 10ns. For obtaining the I_{ds} -transient signal, the drain bias was ramped down from the V_{dq} to a measurement voltage of 1.5V while maintaining the V_{gs} at 0V, similar to what applied during measurement. No thermal effects were considered in the

Fig. 4.15: Differential signals of the I_{ds} transients obtained from the TCAD simulations for individual trap levels of (a) 0.44eV (b) 0.51eV (c) 0.55eV (d) 0.58eV under different V_{dq} stress conditions. Stress time is fixed at 1s and V_{gq} is kept at 0V.

simulation. Thus the model does not account for self-heating effects. Firstly, simulation was performed with STE levels from measurement by considering each trap energy level separately and the differential I_{ds} transient signal are shown in Fig. 4.15 (a)-(d). It is seen that with increasing V_{dq} stress voltage, τ_e although initially increases but quickly saturates for $V_{dq} > 20V$ for all the discrete trap energy levels. This result suggested that the trap activation process occurs while V_{dq} varies from 0 to 20V corresponding to one trap energy level, after which the trap is fully ionized and thus no further change in τ_E .

Fig. 4.16: Differential signals of the I_{ds} transients obtained from the TCAD simulations considering 4 different trap energy levels (MTE model) under different V_{dq} stress conditions. For each V_{dq} stress condition, only one peak is obtained referring to a single effective τ_E .

Next, the MTE model was used considering all the four trap energy levels together and the corresponding differential signal of the I_{ds} transient is shown in Fig. 4.16 for different V_{dq} . Quite surprisingly, the differential signal with MTE model shows only one peak and thus one effective emission time ($\tau_{e,eff}$) although several trap energy levels were considered. The emission time constants extracted from the MTE model ranged between the τ_E of the upper and the lower limits of the incorporated discrete trap energy levels. This clearly reflects that the obtained differential signal actually contains information from various trap energy levels together which were activated under different V_{dq} . To have a clearer picture, a comparison of the τ_E vs V_{dq} characteristics between the experiment and simulation is shown in Fig 4.17. The rate of increase of τ_E with respect to V_{dq} follows a similar trend for both experiment and simulation except with some deviation at high V_{dq} . This deviation is attributed to the self-heating

Fig. 4.17: Emission time constants τ_E vs. V_{dq} stress conditions for MTE model from TCAD (circles), compared with the experimentally obtained emission time constant at 40 °C (diamonds).

effects under experimental conditions which were not considered in the simulation.

The DC trap model presented in the previous sections considered only STE level. As was evident from conductance as well as ON-state stress I_d -transient measurements, there is a strong possibility of the presence of a distribution of trap energies in the energy bandgap at the hetero-interface as well as deep in the GaN buffer. The DC trap model was thus extended to capture the effect of several trap energy levels with some approximations.

For a discrete single quantum energy level, the total trap charge density (Q_{nT}) in the previous model is given by

$$Q_{nT} = qN_{t,A} = qN_t \times F_{t,A} \quad (4.15)$$

$$F_{t,A} = \frac{c_{ns}n + e_{ps}}{c_{ns}n + e_{ns} + c_{ps}p + e_{ps}} \quad (4.15a)$$

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where $F_{t,A}$ is the probability of ionization, c_{ns} , c_{ps} , e_{ns} and e_{ps} are defined previously. In the MTE model, the effective ionized acceptor trap density ($N_{t,A,\text{eff}}$) can be expressed as

$$N_{t,A,\text{eff}} = \sum_{j=1}^m N_{t,A,j} \quad (4.16)$$

where m is the total number of acceptor-like trap levels present in the energy band-gap and $N_{t,A,j}$ is the ionized acceptor trap density for the j^{th} trap energy level. The probability of ionization ($F_{t,A,j}$) and the electron emission rates ($e_{n,A,j}$) for j^{th} trap energy level $E_{t,A,j}$ are given by

$$F_{t,A,j} = \frac{v_n \sigma_{c,n,j} n + e_{p,A,j}}{v_n \sigma_{c,n,j} n + v_p \sigma_{c,p,j} p + e_{n,A,j} + e_{p,A,j}} \quad (4.17)$$

$$e_{n,A,j} = v_n \sigma_{c,n,j} n_i e^{\frac{E_{t,A,j} - E_i}{kT}} \quad (4.17a)$$

Thus, the total trap charge density can be expressed as

$$Q_{nT} = qN_{t,A,\text{eff}} = q(N_{t,1}F_{t,A,1} + \dots + N_{t,m}F_{t,A,m}) \quad (4.18)$$

For GaN HEMTs, hole trapping and detrapping can be neglected as 2DEG n_s is considerably high. Thus, $F_{t,A,j}$ in (4.17) can be approximated as

$$F_{t,A,j} \cong \frac{v_n \sigma_{c,n,j} n}{v_n \sigma_{c,n,j} n + e_{n,A,j}} \quad (4.19)$$

The emission rate $e_{n,A,j}$ can be expressed as

$$\begin{aligned} e_{n,A,j} &= v_n \sigma_{c,n,j} n_i e^{\frac{E_{t,A,j} - E_i}{kT}} \\ &= v_n \sigma_{c,n,j} n e^{\frac{E_{t,A,j} - E_F}{kT}} \\ &= c_{c,n,j} n e^{-D_j/v_{th}} \end{aligned} \quad (4.20)$$

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where $D_j=(E_F-E_{t,A,j})$ is the trap energy referenced to Fermi level and $c_{c,n,j}=v_n\sigma_{c,n,j}$ is the electron capture coefficient of the j^{th} trap level. Thus, the total trap charge density in (4.18) is given by

$$\begin{aligned}
 Q_{nT} &= q(N_{t,1}F_{t,A,1} + N_{t,2}F_{t,A,2} + \dots + N_{t,m}F_{t,A,m}) \\
 &= q\left(\frac{N_{t,1}c_{c,n,1}n}{c_{c,n,1}n + e_{n,A,1}} + \dots + \frac{N_{t,m}c_{c,n,m}n}{c_{c,n,m}n + e_{n,A,m}}\right) \\
 &= q\left(\frac{N_{t,1}c_{c,n,1}n}{c_{c,n,1}n + c_{c,n,1}ne^{-D_1/v_{th}}} + \dots + \frac{N_{t,m}c_{c,n,m}n}{c_{c,n,m}n + c_{c,n,m}ne^{-D_m/v_{th}}}\right) \\
 &= q\left(\frac{N_{t,1}}{1 + e^{-D_1/v_{th}}} + \dots + \frac{N_{t,m}}{1 + e^{-D_m/v_{th}}}\right)
 \end{aligned} \tag{4.21}$$

For compact modeling, Q_{nT} can also be expressed as

$$Q_{nT} = qN_{t,A,\text{eff}} = qN_{t,\text{eff}} \times F_{t,A,\text{eff}} = \left(\frac{qN_{t,\text{eff}}}{1 + e^{-D_{\text{eff}}/v_{th}}}\right) \tag{4.22}$$

where $N_{t,A,\text{eff}}$ is the effective ionized acceptor trap density, $N_{t,\text{eff}}$ is the effective trap density and D_{eff} is the effective trap energy level referenced to Fermi level. Expressing trap densities at each level $N_{t,j}=\kappa_{t,j}N_{t,\text{eff}}$, with $\kappa_{t,j}$ being a proportionality factor, and then equating (4.22) and (4.21), one can express D_{eff} as

$$D_{\text{eff}} = -v_{th} \log\left(\frac{1}{G} - 1\right) \tag{4.23}$$

$$G = \frac{\kappa_{t,1}}{1 + e^{-D_1/v_{th}}} + \frac{\kappa_{t,2}}{1 + e^{-D_2/v_{th}}} + \dots + \frac{\kappa_{t,m}}{1 + e^{-D_m/v_{th}}} = \sum_{j=1}^m \frac{\kappa_{t,j}}{1 + e^{-D_j/v_{th}}} \tag{4.23a}$$

The effective emission rate $e_{n,A,\text{eff}}$ thus can be expressed as

$$e_{n,A,\text{eff}} = c_{c,n,j}ne^{-D_{\text{eff}}/v_{th}} \tag{4.24}$$

Fig. 4.18: Energy band-diagram across AlGaIn/GaN heterostructure with 2 traps $E_{t,A,1}$ & $E_{t,A,2}$. D_j represent the trap energy levels referenced to E_F while $E_{A,j}$ is the corresponding activation energy reference to bottom of conduction band.

Now D_j , the trap energy of j^{th} level reference to Fermi level should be explicitly expressed in order to compute G in (4.23a). From the band diagram in Fig. 4.18, D_j can be expressed as

$$\begin{aligned} D_j &= (E_F - E_{t,A,j}) \\ &= (E_f + V_c + E_{A,j}) \end{aligned} \quad (4.25)$$

where the channel voltage $V_c = V_s$ or V_d at the source or drain ends ($y = 0$ or L_g), respectively, $E_{A,j}$ corresponds to the activation energy of the trap $E_{t,A,j}$, referenced to the bottom of the CB. Now, the drain-bias dependence of the effective emission rate $e_{n,A,\text{eff}}$ and thus time constant $\tau_{e,\text{eff}} (= e_{n,A,\text{eff}}^{-1})$ can be understood from mathematical approach and analysis based on (4.20). Approximately, D_j at the drain end can be expressed from (4.25) as

$$D_j \propto (V_d + E_{A,j}) \quad (4.26)$$

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Thus G from (4.23a) and the effective emission rate from (4.24) can be expressed as

$$G \propto \sum_{j=1}^m \frac{\kappa_{t,j}}{1 + e^{-(V_d + E_{A,j})/V_{th}}} \quad (4.27)$$

$$e_{n,A,\text{eff}} \propto e^{\log\left(\frac{1}{G}-1\right)} \quad (4.28)$$

Although the above analysis incorporated a few approximations, it is an effective way to understand the effect of drain voltage on the emission time constant in the presence of STE and MTE levels. A plot of emission time constant factor from (4.28) w.r.t increasing V_d considering STE and MTE (four different trap levels) is shown in Fig. 4.19(a). It is seen that for STE level, the emission time constant factor ($e_{n,A,\text{eff}}^{-1}$) saturates very quickly with increasing V_d . However, when four different traps were considered with $E_{t,A,j+1} > E_{t,A,j}$, the time constant factor continues to increase and saturates at higher V_d compared to STE. To support this claim, the second order derivative is also shown showing the peak clearly shifted to higher V_d when MTE levels were considered. This behavior completely matches with our experimental data analysis and thus validates the claim for the existence of MTE levels in the GaN bandgap. Finally, the above MTE model was incorporated in our DC trap model and fitted with TCAD simulations for activation energies of (i) 0.3eV ($E_{A,1}$), (ii) 0.4eV ($E_{A,2}$), and (iii) MTE : 0.3eV and 0.4eV ($E_{A,1}$, $E_{A,2}$), as shown in Fig. 4.19(b). The DC trap model with single and multi-trap energy level match nicely with the simulation data, scalable with activation energy without the need of any other parameter tuning.

Fig. 4.19: (a) Variation of emission time constant factor ($e_{n,A,\text{eff}}^{-1}$) from (4.28) and its second order derivative w.r.t drain voltage V_d for different numbers of trap energy level ($m=1-4$). (b) TCAD simulated I_{ds} - V_{gs} fitted with the MTE model (4.22) for 3 different activation energy combinations: (i) 0.3eV ($E_{A,1}$) (ii) 0.4eV ($E_{A,2}$) and (iii) MTE : 0.3eV and 0.4eV ($E_{A,1}$, $E_{A,2}$).

4.3. Pulsed I-V modeling

The previous section presented a DC trap model which considers the ON-state trapping mechanism. However, GaN devices are mostly intended for high power switching applications where the device is stressed for a finite amount of time (T_{off}) with low V_{gs} and high V_{ds} (V_{gq} , V_{dq}) which is the OFF-state condition. In the next cycle, device is switched on with low V_{ds} , to operate in the linear region as shown in Fig. 4.20. Thus apart from DC model, the effect of V_{gq} , V_{dq} and the stress time T_{off} on the ON-state drain current should also be modeled using OFF-state pulsed I - V measurements [122]–[124].

4.3.1. Off-state stress : possible trap locations

Before proceeding to model the effect of gate and drain quiescent biases on the I - V characteristics, it is important to understand the location of the traps under particular OFF-state stress. In the OFF-state, high gate-drain electric field induces both temporary and permanent current-collapse due to electron trapping and mechanical strain in GaN HEMTs. The current model only focuses

Fig. 4.20: Representation of a pulsed I - V measurement method with pulse width of 200ns and pulse separation of 1s (T_{off}) for a gate and drain quiescent bias of (V_{gq} , V_{dq}) = (-5, 40) V and ON-state measurement condition of V_{gs} =0V and V_{ds} =1.5V. (Time & measurement points not to scale)

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on the “recoverable current collapse” and temperature dependent I_{ds} transient measurements were used to study those trap properties.

The GaN HEMT structure under study has an L_{gd} of 6 μm , L_{gs} and L_g of 2 μm . The temperature dependent I_{ds} transient measurements (from 20°C to 120°C, increment of 20°C) were performed using Agilent 1505A power device analyser. The devices were stressed with $V_{gq} = -5\text{V}$ and $V_{dq} = 40\text{V}$ for $T_{off} = 1\text{s}$. The detrapping signal was then measured at $V_{gs} = 0\text{V}$ and $V_{ds} = 1.5\text{V}$. The $V_{ds} = 1.5\text{V}$ was chosen to eliminate the influence of self-heating effects during measurements. Fig. 4.21(a) shows the measured I_{ds} transient normalized to steady-state value at different temperatures. The corresponding differential signals are plotted in Fig. 4.21(b). The devices exhibited a thermally activated detrapping mechanism, with activation energy (E_A) of $0.33 \pm 0.05\text{eV}$ and capture cross-section of $1.2 \times 10^{-20} \text{cm}^2$, obtained from Arrhenius plot as shown in the inset. The observed trap with $E_A = 0.33\text{eV}$ is commonly accepted to be located in AlGaIn barrier [58, 114]. Under negative gate-bias, electrons tunnel through the gate contact [6], [126]–[129] into the AlGaIn barrier by a tunnelling-assisted Poole-Frenkel (TAPF) conduction mechanism as shown in Fig. 4.22. The thermally activated emission rate (e_n) is described by the Arrhenius expression with the field dependent activation energy,

$$e_n \propto \exp \left[-\frac{E_{T0} - \Delta\phi_{PF}}{KT} \right] \quad (4.29)$$

where E_{T0} is the zero-field ionization energy. With an extracted E_{T0} of 0.54eV and potential-well-height lowering ($\Delta\phi_{PF}$) of $\sim 0.2\text{--}0.25\text{eV}$ under gate-lag condition as reported in [6], the effective activation energy closely matches with experimentally determined E_A (0.33eV) from current devices under test.

Fig. 4.21: (a) Temperature dependent normalized I_{ds} transients of GaN HEMT with device dimensions: $L_{gs}/L_g/L_{gd}/W_g = 2/2/6/80 \mu\text{m}$ after an off-state stress of $(V_{gq}, V_{dq}) = (-5, 40) \text{ V}$. (b) The corresponding differential signals at different temperature; Inset Arrhenius plots for determining the activation energy (E_A).

4.3.2. Pulsed I-V model: gate lag

The most pronounced effect of deep level traps in AlGaIn/GaN HEMTs under OFF-state stress condition is the '*gate-lag*' effect, whereby, the gate is stressed for stress time T_{off} at a certain quiescent bias (V_{gq}) while the drain bias is not varied. In general, for GaN HEMTs, traps can be located mainly in three distinct regions such as the surface, the AlGaIn barrier, or the GaN buffer. Initial reports attributed gate-lag to surface donor states [130]. By virtue of highly optimized passivation schemes, the effect of surface states had been considerably alleviated in the state-of-the-art devices. Current research shows that other mechanisms may also be responsible for the gate-lag effect. Simin et. al. [131] showed that, under gate-lag condition, the current collapse results from increased source–gate and gate–drain resistances but not from the channel resistance under the gate. The increase in access region resistance was linked to the decrease in piezoelectric charge resulting from the gate-bias-induced nonuniform strain in the AlGaIn barrier. However, as will be seen later,

Fig. 4.22: (a) HEMT cross-section showing possible regions of trapping under gate-lag condition ($V_{\text{gq}}, V_{\text{dq}} = (-5, 0)$). Trapping under the gate will affect the threshold voltage V_{off} . (b) Trap assisted Poole-Frenkel mechanism for electron emission from traps in the AlGaIn barrier [6].

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the fabricated GaN devices [5] exhibited hardly any dyn- $R_{DS,ON}$ degradation but a considerable threshold voltage shift (ΔV_{off}) under gate-lag condition. This improvement can possibly be due to Ammonium-Sulphide treatment followed by Si_3N_4 passivation in the extrinsic regions [5]. As reported in [132]-[133], gate-lag condition may result in trapping at the gate edge or in the deep buffer. On the other hand, DasGupta et. al. [134] suggested that electrons from the 2DEG are rolled back into the buffer by the negative gate bias and buffer Carbon is responsible for the trapping-induced ΔV_{off} shift. As the devices under test are not intentionally Carbon-doped, it is concluded that the gate-lag effect is largely due to traps present in the AlGaN barrier under the gate. The previous section also supports this claim about trap locations in AlGaN barrier under OFF-state stress condition. Considering these factors, a compact model that takes into account the effect of gate quiescent bias V_{gq} and OFF-state time T_{off} will be presented in the next section.

Fig. 4.23: Simulated pulsed I_{ds} - V_{ds} characteristics (symbol) of HEMT, fitted with the base model as presented in chapter 2 (solid line). The gate and drain quiescent bias are fixed at $(V_{gq}, V_{dq}) = (0, 0)$ V which is a “cold condition” ensuring minimal trapping effects.

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The key step is to extract the threshold voltage V_{off} and fit the model with pulsed $I_{\text{ds}}-V_{\text{ds}}$ and $I_{\text{ds}}-V_{\text{gs}}$ with quiescent bias of $V_{\text{gq}} = V_{\text{dq}} = 0\text{V}$, as this condition ensures minimum trapping phenomena (cold bias condition). For model formulation and validation, pulsed $I-V$ simulation was done in TCAD by considering acceptor traps in the AlGaIn barrier. The dynamic traps were modeled in TCAD by a Shockley-Read-Hall recombination term included in the continuity equation. The universal Schottky tunneling model was considered to model the gate leakage. To extract pulsed $I-V$ data from the transient simulations, drain current values were obtained just $0.2 \mu\text{s}$ after device was switched on to ensure minimal electron emission as well as to neglect any ON-state trapping events. The core model without trapping was then fitted with the pulsed $I-V$ so as to ensure calibrated model is free from trapping effects with an extracted V_{off} of -3.6V as shown in Fig. 4.23.

Under gate-lag condition, tunneled electrons from gate can be trapped at the surface via surface hopping or in the AlGaIn barrier via tunneling. Due to improved surface passivation, trapping at the surface has been restrained to a great extent, and thus the trapping of electrons in the AlGaIn barrier under the gate becomes the most prominent mechanism as was discussed in the previous section. As majority of the trapping occurs under the gate, the final threshold voltage is given by [135]

$$V_{\text{off,finl}} = V_{\text{off}} + \Delta V_{\text{off}} \quad (4.30)$$

ΔV_{off} can be computed considering simple first order trap kinetics from [135]

$$\frac{d\Delta V_{\text{off}}}{dt} = \frac{\Delta V_{\text{off,MAX}} - \Delta V_{\text{off}}}{\tau_c} \quad (4.31)$$

Fig. 4.24: Simulated pulsed I_{ds} - V_{ds} characteristics (symbol) of HEMT, fitted with the model using (4.32) (dashed line) with varying stress time T_{off} for extraction of capture time τ_C . The gate and drain quiescent biases are fixed at $(V_{gq}, V_{dq}) = (-5, V_{ds})$ V.

where $\Delta V_{off,MAX}$ is the maximum shift in the V_{off} , and τ_C is the capture time constant. Solving (4.31), ΔV_{off} can be expressed as

$$\Delta V_{off} = \Delta V_{off,MAX} (1 - e^{-t/\tau_C}) \quad (4.32)$$

To extract τ_C , T_{off} was varied from microseconds to seconds with a fixed V_{gq} of -5 V and the corresponding pulsed I_d - V_{ds} was extracted as shown in Fig. 4.24. Considering (4.32) in the model, τ_C and $\Delta V_{off,MAX}$ were extracted for that particular $V_{gq} = -5$ V and for the measurement V_g of 0 V. The same sets of extracted values were used to predict the pulsed data with measurement V_g of -1 V and nice match was observed. Although τ_C normally remains independent of V_{gq} [136], $\Delta V_{off,MAX}$ varies with V_{gq} as expected. This variation with V_{gq} was assumed to be linear in deep subthreshold region but non-linear in the near threshold region. So, $\Delta V_{off,MAX}$ can be given by

Fig. 4.25: Variation of V_{Qeff} , V_{STEP} , and $V_{gq,act}$ calculated from (4.34)–(4.35) with respect to V_{gq} for different values of α_h . V_{off} was extracted to be -3.671 V.

$$\Delta V_{off,MAX} = \alpha_t \cdot V_{gq,act} \quad (4.33)$$

where α_t is the linearity factor, and $V_{gq,act}$ is the effective gate quiescent bias. When V_{gq} is less than V_{off} , $\Delta V_{off,MAX}$ follows (4.33) with $V_{gq,act} = V_{gq}$. However, when V_{gq} is more than V_{off} , $\Delta V_{off,MAX}$ follows (4.33) with $V_{gq,act} \sim '0'$ as the capture process is not dominant because of negligible gate tunneling current. To model this effect, $V_{gq,act}$ is expressed as

$$V_{gq,act} = V_{STEP} \cdot V_{gq} \quad (4.34)$$

where V_{STEP} is a step function equal to '1' when V_{gq} is less than V_{off} ; otherwise it tends to '0'. It is given by

$$V_{STEP} = \tanh(V_{Qeff} / \alpha_h) \quad (4.35)$$

$$V_{Qeff} = 0.5 \left(- (V_{gq} - V_{off}) + \sqrt{(V_{gq} - V_{off})^2 + 4\epsilon_t} \right) \quad (4.35a)$$

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where ε_t is a smoothing parameter. When V_{gq} is higher than V_{off} , the smoothness with which $V_{gq,act}$ returns to '0' is determined by α_h . As shown in Fig. 4.25, $V_{gq,act}$ follows V_{gq} in the deep subthreshold region and gradually turns to '0' in the near threshold region. For extraction of α_t and α_h , V_{gq} was varied from -2 V (onset of inversion) to -7 V (deep subthreshold) for a fixed T_{off} of 50 ms and the model was fitted with pulsed I_d - V_{ds} as plotted in Fig. 4.26. Recalling the threshold voltage of the device to be -3.6V, as V_{gq} changes from -3 to -2V a sudden drop in the pulsed drain is observed. This is where the effect of $V_{gq,act}$ and α_h comes into play.

For gate-lag model validation, the extracted parameters α_t and α_h were used to predict pulsed I_{ds} - V_{ds} for different V_{gq} and a T_{off} of 20ms from TCAD simulation. A good match with numerical simulation is obtained, as shown in

Fig. 4.26: Simulated pulsed I_{ds} - V_{ds} characteristics (symbol) of HEMT, fitted with the model (dashed line) for a wide range of V_{gq} for extraction of α_t and α_h . T_{off} was fixed at 50ms.

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Fig. 4.27(a). Fabricated HEMT devices were also used to validate the gate-lag model. The sample HEMT has a 2.5-nm GaN cap layer, an 18-nm AlGaIn barrier layer, a 2.4- μm GaN layer, and nucleation layer on a high-resistivity Si substrate. The measured device has a 2 μm gate length and an 80 μm gate width. L_{gs} and L_{gd} are both 2 μm . The model was compared with the pulsed I - V measurements carried out using Agilent B1505, under different V_{gq} for a fixed T_{off} of 500ms, and is shown in Fig. 4.27(b). As mentioned before, due to improved surface passivation scheme, the $\text{dyn-}R_{\text{DS,ON}}$ degradation is not a severe concern under gate-lag condition. The model is able to predict pulsed I - V characteristics from both TCAD and measurements, showing good scalability with V_{gq} and T_{off} .

Fig. 4.27: (a) Simulated pulsed I_{ds} - V_{ds} characteristics (symbol) of HEMT, compared with the predicted model (solid line) with extracted values of α_i and α_h for a wide range of V_{gq} . T_{off} was fixed at 20ms. (b) Measured pulsed I_{ds} - V_{ds} characteristics (symbol) fitted with the model (line) for varying V_{gq} . T_{off} was fixed at 500ms for all measurements.

4.3.3. Pulsed I-V model: both-lag

After characterizing and modeling the gate-lag, the effect of drain quiescent bias (V_{dq}) is also modeled semi-empirically. Although devices under gate-lag show no significant change in $\text{dyn-}R_{DS,ON}$, devices under both gate- and drain-lag conditions resulted in severe trapping in the gate-drain access region, affecting the linear I_{ds} - V_{ds} characteristics due to high drain electric field. At high V_{dq} , surface states in the extrinsic gate-drain access region capture tunneled gate electrons which, in turn, hop towards the drain under the influence of high electric field as shown in Fig. 4.28. The electron hopping probability in surface states increases with increasing electric field but saturates at some critical voltage [83]. Drain-lag measurement was done on AlGaIn/GaN HEMT with $L_g=L_{gs}=2\mu\text{m}$ and $L_{gd}=10\mu\text{m}$ and a stress time of 500ms. With a constant $V_{gq}=-$

Fig. 4.28: HEMT cross-section showing possible regions of trapping under gate- and drain-lag condition (V_{gq}, V_{dq}) = (-5, 40) V. Trapping in the extrinsic access region will affect the $\text{dyn-}R_{DS,ON}$. For measurement, L_{gd} was varied from 2 to $10 \mu\text{m}$.

Fig. 4.29: Measured transient drain current in linear region for fixed V_{gq} and varying V_{dq} , showing that the current-collapse saturates at some critical electric field.

5V, as V_{dq} is increased from 0V-120V, dyn- $R_{DS,ON}$ increases but saturates at high V_{dq} as observed in the transient measurement of Fig. 4.29.

Under both gate- and drain-lag conditions, tunneled gate electrons get trapped in the surface states and deplete the 2DEG in the access region, resulting in high dyn- $R_{DS,ON}$. Considering a semi-empirical approach, it can be inferred that the effective 2DEG density σ_{eff} in the access region (polarization charge density) is not constant under this condition; instead, it is V_{dq} dependent. The effective charge density can be expressed as

$$\sigma_{eff} = \sigma_o - n_t = \sigma_o - \sigma_m \left(1 - e^{-\alpha_D V_{dq}/V_{th}} \right) \quad (4.36)$$

$$\sigma_{eff} \left(\text{High } V_{dq} \right) = \sigma_o - \sigma_m \quad (4.36a)$$

where σ_o is the polarization charge density with no trapping effect, n_t is the trapped charge density, σ_m is the maximum trapped charge density, and α_D is a

TABLE VI
PULSED I-V: EXTRACTED MODEL PARAMETERS

Parameter	TCAD	Measurement
α_t (N.A): Gate-lag	-8.36×10^{-3}	-1.35×10^{-3}
α_h (V): Gate-lag	5×10^{-3}	5×10^{-3}
ε_i (V ²): Gate-lag	1×10^{-3}	1×10^{-3}
σ_m (cm ⁻²): Both-lag	4.5×10^{12}	6.34×10^{12}
α_D (N.A): Both-lag	7.2×10^{-4}	2.6×10^{-3}

fitting parameter. The new 2DEG density σ_{eff} can be used to recalculate the drain access resistance R_d from (2.74) in chapter 2 which is given below as

$$R_d = \frac{L_{gd}}{qW\mu_{rd}\sigma_{\text{eff}}} \left(1 + \xi_{rd} \left(\frac{\mu_{rd}(V_d - V_{di})}{v_{\text{satd}}L_{gd}} \right)^2 \right)^{\frac{1}{2}} \quad (4.37)$$

The methodology is first to extract σ_m from the pulsed I_{ds} - V_{ds} data using (4.36a) corresponding to high values of V_{dq} . The variation of dyn- $R_{DS,ON}$ with a different V_{dq} is then modeled by accurate extraction of α_D . Effect of different V_{dq} on the current-collapse is well captured by the above model matched with numerical simulation as shown in Fig. 4.30. For devices subjected to both gate/drain-lag conditions, the model was validated with measured data from AlGaN/GaN HEMT as well for different values of V_{dq} as shown in Fig. 4.31. Under both gate/drain-lag conditions, V_{gq} was fixed at -10 V with a stress time T_{off} of 500 ms. As stated earlier, the drain current initially reduces with increasing V_{dq} but the rate decreases at some critical V_{dq} . With extraction of σ_m and α_D , the model for both-lag, although empirical in nature, is able to capture the dyn- $R_{DS,ON}$ degradation with V_{dq} for devices with different L_{gd} . A list of all the model parameters used for fitting the gate- and gate/drain-lag model with pulsed I - V characteristics for both TCAD and measurement data is shown in Table VI.

Fig. 4.30: Gate/drain lag: Simulated pulsed I_{ds} - V_{ds} characteristics (symbol) fitted with the model (dashed line) with $V_{gq} = -5 \text{ V}$ and varying V_{dq} . T_{off} is fixed at 20ms.

Fig. 4.31: Gate/drain lag: Measured pulsed I_{ds} - V_{ds} characteristics (symbol) fitted with the model (solid/dashed line) with $V_{gq} = -10 \text{ V}$ and varying V_{dq} for two different L_{gd} ($2 \mu\text{m}$ and $10 \mu\text{m}$). T_{off} is fixed at 500 ms for all measurements.

4.4. Transient model

The model presented in the previous section accounts for the extent of current-collapse, i.e., the trapping of electrons. However, the detrapping process with time also needs to be modeled for accurate transient simulations. A popular approach is to use a separate RC sub-circuit for capture and emission processes [136], [137]. Although suitable for small signal simulations, the RC sub-circuit approach is not accurate for large signal modeling. An alternative method of modeling output conductance dispersion was reported in [138] but did not account for transient simulation. In this work, a phenomenological approach is to use a single differential equation valid for both capture and emission processes. For electron-trapping process, (4.31) is followed that considers the effect of capture time τ_C . The emission of electrons can be modeled using first order kinetics [138] given by

$$\frac{d\Delta V_{\text{off}}}{dt} = -\frac{\Delta V_{\text{off}}}{\tau_E} \quad (4.38)$$

where τ_E is the emission time constant that can be obtained from (4.2a). Under gate-lag condition during stress time, tunneled gate electrons get trapped in the AlGaIn barrier resulting in ΔV_{off} -shift. During the next phase, i.e., ON-state, these tunneled electrons emit from the traps whereby eq. (4.38) applies. For transient simulation in Verilog-A, it is necessary to have a single equation able to capture trapping (4.31) and detrapping (4.38) phenomena during OFF-state and ON-state condition separately as given by

$$\frac{d\Delta V_{\text{off}}}{dt} = \frac{\Delta V_{\text{off,MAX}} \left(1 - V_{\text{go,act}} / V_{\text{go}}\right) - \Delta V_{\text{off}}}{\tau_C \left(1 - V_{\text{go,act}} / V_{\text{go}}\right) + \tau_E \left(V_{\text{go,act}} / V_{\text{go}}\right)} \quad (4.39)$$

Fig. 4.32: Simulated transient I_{ds} (line) from Verilog-A by solving (4.38) compared with TCAD (circles). Also shown is the variation of ΔV_{off} for V_{gq} of -4 and -7 V computed from Verilog- A.

$$V_{go,act} = 0.5 \left(V_{go} + \sqrt{V_{go}^2 + 4\varepsilon_{tr}} \right) \quad (4.39a)$$

where ε_{tr} is a smoothing parameter. Thus when $V_g < V_{off}$, (4.39) follows (4.31) and for ON-state condition, (4.39) follows (4.38). Verilog-A compiler was used to solve (4.39) for transient simulation with $\Delta V_{off,MAX}$ extracted from pulsed I - V measurements. Transient simulations from TCAD were used to validate the dynamic nature of the model for a $T_{off} = 20\text{ms}$ and different V_{gq} as shown in Fig. 4.32. The variation of ΔV_{off} with time extracted from Verilog-A is also plotted showing the capture and emission processes explicitly. With obtained τ_E from (4.2a), the model is able to capture the emission process quite accurately. As explained before, simulated $\Delta V_{off,MAX}$ is directly proportional to V_{gq} . A model playback was run in CADENCE for two values of τ_E ($10\ \mu\text{s}$ and $100\ \mu\text{s}$) under gate-lag condition and the transient simulation plots are shown in Fig. 4.33. The change in τ_E is captured by the above transient model.

(a)

(b)

Fig. 4.33: Model playback of the transient drain current model from Verilog-A for τ_E of (a) $10 \mu s$ and (b) $100 \mu s$. (V_{gq} , V_{dq}) was set at $(-10, 0)$ V while ON-state measurement condition was set at $(V_{gs}, V_{ds}) = (0, 5)$ V.

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The compact nature of the transient model is attributed to the fact that the ΔV_{off} -shift with time is computed internally while modeling surface potential and does not require external and more complex RC sub-circuit approach. The developed transient model is found to be scalable over major trap-related parameters such as capture/emission time (τ_C/τ_E), gate quiescent bias (V_{gq}) and stress time (T_{off}).

4.5. Conclusion

In the first part of this chapter, a comprehensive trap-charge model was included in the surface-potential-based compact model to explore the effects of AlGaIn/GaN interface traps on the HEMT device characteristics. Based on an iterative approach, the interface-trap-density-dependent surface potential was formulated, which was used for the DC current modeling. The presence of MTE states in the GaN energy band-gap was validated using conductance method as well as drain current transient under ON-state stress condition. The DC trap model was extended to incorporate the effects of MTE levels.

In the second part of this chapter, a semi-empirical current-collapse model, capturing the effects of gate and drain quiescent biases, was also presented and validated with pulsed measurements and numerical simulations. The capture/emission of electrons under gate lag was modeled in Verilog-A for transient simulations, which can be a better alternative than the RC sub-circuit approach. The methodology presented in this chapter provides a broad platform for designing next generation III–V-on-Si co-integrated ultra-large scale integration systems for high-frequency applications as well as reliability studies.

Chapter 5: Conclusion & Recommendations

5.1. Conclusion

A single-piece unified model for the 2DEG charge density and the Fermi potential in the triangular well formalism that is valid from strong-inversion (with two subbands) to moderate-inversion and subthreshold regions has been developed in this work. The inclusion of moderate-inversion regional model has shown advantages in capturing the essential physical behaviors in heterostructure HEMTs. The explicit E_f model, which relates to the surface potential ϕ_s can be extended directly to a ϕ_s -based terminal current (and charge) model for generic HEMT/MIS-HEMT compact modeling.

The next part of the thesis is focused on the effect of GaN buffer doping on the surface potential as well as subthreshold current behavior of GaN HEMTs. Due to the low-doping of the UID body in HEMTs, subthreshold characteristics show bias-dependent slope as a result of thick-body effect. This is modeled similar to partially-depleted SOI core model with quasi-2D Poisson solution for the 2D electrostatics included in the bias/geometry-dependent DIBL and flatband-shifted gate voltage, which is adapted to the generic HEMT model. The proposed model has the unique feature of realizing classical charge-voltage equation with buffer doping in the subthreshold region and coupled P-S

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solution in the moderate- and strong-inversion regions, with which it is possible to model the subthreshold current characteristics in short-channel HEMT devices.

The calibrations for both charge and drain current are explained in the third chapter. It has been demonstrated that both the charge and drain current models are able to fit and predict for different geometries and biases physically. The model calibration approach in this thesis has shown promising capabilities in leveraging model development for conventional Si-CMOS and extending to III–V-based emerging devices for hybrid designs in future generation III–V/Si co-integrated ULSI systems.

The final chapter explored the effects of AlGaIn/GaN interface traps on HEMT device characteristics whereby an interface-trap model is included in the surface-potential-based compact model. Based on an iterative approach, the trap-density-dependent surface potential is presented, which is used for DC current modeling. A semi-empirical current-collapse model capturing the effects of gate and drain quiescent biases is also presented and validated with pulsed measurements and numerical simulations. The capture/emission of electrons under gate-lag is modeled in Verilog-A for successful transient simulations, which can be a better alternative than the RC-subcircuit approach. This will benefit the circuit designers in reducing design complexity as well as studying transient trap-charge effects.

The trap model presented in this thesis is different from existing models in the way that this work tries to focus more on a complete model that includes both DC trapping due to interface traps as well as trapping due to gate- and gate/drain-lag stress conditions in pulsed measurements. This gives circuit

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designers a complete understanding of the model behaviors under varied quiescent-bias conditions and stress time. In this way, separating the various trapping events, the model formulation becomes very simple in nature to understand, and it is easy to implement in Verilog-A environment.

Finally, it must be noted that the proposed model in this work, although based on AlGaIn/GaN HEMT, is also a generic model that can be applied to any material heterostructure combination with a triangular quantum well. As the model considers the material properties in the ' V_{off} ' and ' C_d ' expressions, it is easy to implement this model for other III-V systems. Also, as mentioned earlier, the model is based on GaN-on-Silicon substrate. However, it must be understood that the substrate will affect the GaN HEMT characteristics in following ways:

- (a) Substrate material determines the substrate conductivity which, in turn will affect the thermal resistance. The self-heating effect is modelled with thermal resistance R_{th} as the tuning parameter.
- (b) Thermo-mechanical stress in the buffer may affect the sheet polarization charge density at the AlGaIn/GaN interface. In our model, the polarization charge is included in the V_{off} as well as the source/drain access resistance expressions R_c . So, any change in thermo-mechanical stress, can be effectively captured by the model.
- (c) Substrate material also determines the type of crystal defects that will affect the pulsed I - V characteristics. Under both-lag condition, with buffer traps playing a significant role, the quality of substrate determines the extent of current-collapse. The proposed gate- and both-lag model is based on

Chapter 5: Conclusion & Recommendations

extracting the model parameters from pulsed I-V characteristics. Any change in substrate, will definitely have impact on the extracted model parameters.

Thus, the model can also be used for GaN-on-other substrates, provided the parameter extraction methodology is correctly implemented.

5.2. Recommendation

The following works are recommended for future study.

1. The 2DEG capacitance model does not include the parallel channel effects for MIS-HEMTs where a second hump is observed at high gate bias. The n_s-E_f model can be extended for capacitance modeling to include the parallel channel with careful consideration of the model smoothness.
2. The charge model developed is limited to the length dimension. For short-channel devices, parasitic capacitance dominates and should be taken into consideration to develop the short-channel charge model.
3. The forward and reverse gate-leakage model presented is valid for 2-terminal diode structures. However, for 3-terminal FET devices, correct V_{ds} dependency should be incorporated using the surface potential solution at the source and drain ends.
4. As GaN HEMTs are more promising for high power devices, accurate breakdown voltage models can be proposed.
5. Field-plate GaN HEMTs is a popular structure for high breakdown voltage devices. The current model can be extended to include the effects of field plates with dimension scaling.

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6. The effect of temperature on trap dynamics due to self-heating can be modeled by conventional thermal-resistance approach. Following the extraction of capture and emission times, τ_C and τ_E can be related to temperature based on the Arrhenius equation, in which the reaction rates are proportional to $T^2 \exp(-E_A/kT)$, where E_A is the trap activation energy. Further study can be done to incorporate E_A as a model parameter, from which the temperature dependency can be effectively captured.
7. The transient model presented only includes the gate-lag effects. The drain-lag effects can be incorporated to include the effect of drain quiescent bias V_{dq} .
8. Although only tunneling mechanisms are considered in this model, hot-electron injections in ON-state as well as substrate current injection in the blocking state also contribute to current collapse, which requires further investigations.

Publications

Publications

Journal

Principle Author

1. B. Syamal, X. Zhou, S. B. Chiah, A. M. Jesudas, S. Arulkumaran, and G. I. Ng, "A comprehensive compact model for GaN HEMTs, including quasi-steady-state and transient trap-charge effects," *IEEE Trans. Electron Devices*, vol. 63, no. 4, pp. 1478–1485, 2016.

Co-author

1. J. Zhang, B. Syamal, X. Zhou, S. Arulkumaran, and G. I. Ng, "A compact model for generic MIS-HEMTs based on the unified 2DEG density expression," *IEEE Trans. Electron Devices*, vol. 61, no. 2, pp. 314–323, 2014.
2. M. J. Anand, G. I. Ng, S. Arulkumaran, C. M. Manoj Kumar, K. Ranjan, S. Vicknesh, S. C. Foo, B. Syamal, and X. Zhou, "Effect of OFF-state stress induced electric field on trapping in AlGaIn/GaN high electron mobility transistors on Si (111)," *Appl. Phys. Lett.*, vol. 106, no. 8, 2015.
3. M. J. Anand, G. I. Ng, S. Arulkumaran, B. Syamal, and X. Zhou, "Distribution of trap energy level in AlGaIn/GaN high-electron-mobility transistors on Si under ON-state stress," *Appl. Phys. Express*, vol. 8, no. 10, 2015.

Conference

Principle Author

1. B. Syamal, S. Ben Chiah, X. Zhou, A. Ajaykumar, M. J. Anand, G. I. Ng, and S. Arulkumaran, "GaN HEMT compact model for circuit simulation," *Proc. 2015 IEEE Int. Conf. Electron Devices Solid-State Circuits, EDSSC 2015*, vol. 2, no. 3, pp. 535–538, 2015.

Co-author

1. X. Zhou, J. Zhang, B. Syamal, S. Ben Chiah, H. Zhou, and L. Yuan, "Unified regional modeling of GaN HEMTs with the 2DEG and DD

Publications

- formalism,” in *ICSICT 2012 - 2012 IEEE 11th International Conference on Solid-State and Integrated Circuit Technology, Proceedings*, 2012.
2. X. Zhou, J. Zhang, B. Syamal, Z. Zhu, H. Zhou, and S. B. Chiah, “Top-down drift-diffusion versus bottom-up quasi-ballistic formalism in device compact modeling,” in *Proceedings of the 20th International Conference on Mixed Design of Integrated Circuits and Systems, MIXDES 2013*, 2013, p. 53.
 3. X. Zhou, J. B. Zhang, B. Syamal, Z. M. Zhu, and L. Yuan, “A scalable compact model for generic HEMTs in III-V/Si co-integrated hybrid design,” *2013 IEEE Int. Conf. Electron Devices Solid-State Circuits, EDSSC 2013*, pp. 4–5, 2013.
 4. X. Zhou, S. B. Chiah, B. Syamal, H. T. Zhou, A. Ajaykumar, and X. Liu, “Compact model characteristics for generic MIS-HEMTs,” in *Technical Proceedings of the 2014 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2014*, 2014, vol. 2, pp. 495–498.
 5. X. Zhou, S. B. Chiah, B. Syamal, A. Ajaykumar, X. Liu, and H. Zhou, “Compact modeling of III-V/Si FETs,” in *Proceedings - 2014 IEEE 12th International Conference on Solid-State and Integrated Circuit Technology, ICSICT 2014*, 2014.
 6. A. Ajaykumar, Z. Xing, B. Syamal, and S. Ben Chiah, “Compact Fermi potential model for heterostructure HEMTs with rectangular quantum well,” in *European Solid-State Device Research Conference*, 2014, pp. 266–269.
 7. A. Ajaykumar, X. Zhou, B. Syamal, S. Ben Chiah, and L. Zhang, “Compact electrical/optical model for InGaN/GaN quantum-well based LEDs,” in *Proceedings of the 2015 IEEE International Conference on Electron Devices and Solid-State Circuits, EDSSC 2015*, 2015, pp. 766–769.

References

References

- [1] J. Yoshida, "Classical Versus Quantum Mechanical Calculation of the Electron Distribution At the N-AlGaAs/GaAs Heterointerface.," *IEEE Trans. Electron Devices*, vol. ED-33, no. 1, pp. 154–156, 1986.
- [2] D. Delagebeaudeuf and N. T. Linh, "Metal-(n) AlGaAs-GaAs two-dimensional electron gas FET," *IEEE Trans. Electron Devices*, vol. 29, no. 6, pp. 955–960, 1982.
- [3] J. Zhang, B. Syamal, X. Zhou, S. Arulkumaran, and G. I. Ng, "A compact model for generic Mis-hemts based on the unified 2deg density expression," *IEEE Trans. Electron Devices*, vol. 61, no. 2, pp. 314–323, 2014.
- [4] D. Yan, J. Jiao, J. Ren, G. Yang, and X. Gu, "Forward current transport mechanisms in Ni/Au-AlGaIn/GaN Schottky diodes," *J. Appl. Phys.*, vol. 114, no. 14, 2013.
- [5] M. J. Anand *et al.*, "Effect of OFF-state stress induced electric field on trapping in AlGaIn/GaN high electron mobility transistors on Si (111)," *Appl. Phys. Lett.*, vol. 106, no. 8, 2015.
- [6] O. Mitrofanov and M. Manfra, "Poole-Frenkel electron emission from the traps in AlGaIn/GaN transistors," *J. Appl. Phys.*, vol. 95, no. 11 I, pp. 6414–6419, 2004.
- [7] R. J. Trew, "SiC and GaN transistors - Is there one winner for microwave power applications?," *Proc. IEEE*, vol. 90, no. 6, pp. 1032–1047, 2002.
- [8] U. K. Mishra, L. Shen, T. E. Kazior, and Y. F. Wu, "GaN-based RF power devices and amplifiers," *Proc. IEEE*, vol. 96, no. 2, pp. 287–305, 2008.
- [9] X. Zhou *et al.*, "Unified Compact Modeling of Emerging Multiple-Gate MOSFETs," *2007 Int. Work. Electron Devices Semicond. Technol.*, pp. 31–36, 2007.
- [10] S. C. Binari, J. M. Redwing, G. Kelner, and W. Kruppa, "AlGaIn/GaN HEMTs grown on SiC substrates," *Electron. Lett.*, vol. 33, no. 3, p. 242, 1997.
- [11] S. N. Mohammad, A. A. Salvador, and H. Morkoc, "Emerging gallium nitride based devices," *Proc. IEEE*, vol. 83, no. 10, pp. 1306–1355, 1995.
- [12] T. P. Chow *et al.*, "SiC and GaN bipolar power devices," *Solid. State. Electron.*, vol. 44, no. 2, pp. 277–301, 2000.
- [13] J. C. Gerbedoen, A. Soltani, J. C. De Jaeger, and C. Yvon, "High transconductance on AlGaIn/GaN HEMT on (110) silicon substrate," *Eur. Microw. Week 2012 "sp. Microwaves", EuMW 2012, Conf. Proc. - 7th Eur. Microw. Integr. Circuits Conf. EuMIC 2012*, no. 110, pp. 413–416, 2012.
- [14] M. Ishida, T. Ueda, T. Tanaka, and D. Ueda, "GaN on Si technologies for power dwitching fevices," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3053–3059, 2013.
- [15] F. Medjdoub, *Gallium Nitride (GaN): Physics, Devices, and Technology*. CRC Press, 2015.
- [16] M. S. Shur and R. F. Davis, *GaN-Based Materials and Devices: Growth, Fabrication, Characterization and Performance*. Selected Topics in Electronics and Systems, 2004.
- [17] Y. Taur *et al.*, "CMOS scaling into the nanometer regime," *Proc. IEEE*, vol. 85, no. 4, pp. 486–503, 1997.
- [18] M. Redzuan *et al.*, "Mesh grid of SILVACO TCAD effect on net doping profile for NMOS structures," in *AIP Conference Proceedings*, 2009, vol. 1136, pp.

References

- 581–585.
- [19] C. T. Sah, “The Equivalent Circuit Model in Solid-State Electronics??Part I: The Single Energy Level Defect Centers,” *Proc. IEEE*, vol. 55, no. 5, pp. 654–671, 1967.
 - [20] J. R. Brews, “A charge-sheet model of the MOSFET,” *Solid State Electron.*, vol. 21, no. 2, pp. 345–355, 1978.
 - [21] T. H. Morshed *et al.*, “BSIM4v4 . 7 MOSFET Model -User ’ s Manual Developers :,” *Bsim470*, 2011.
 - [22] J. He, X. Xi, H. Wan, M. Dunga, M. Chan, and A. M. Niknejad, “BSIM5: An advanced charge-based MOSFET model for nanoscale VLSI circuit simulation,” *Solid. State. Electron.*, vol. 51, no. 3, pp. 433–444, 2007.
 - [23] K. Joardar, K. K. Gullapalli, C. C. McAndrew, M. E. Burnham, and A. Wild, “An improved MOSFET model for circuit simulation,” *Electron Devices, IEEE Trans.*, vol. 45, no. 1, pp. 134–148, 1998.
 - [24] M. Miura-Mattausch, U. Feldmann, A. Rahm, M. Bollu, and D. Savignac, “Unified complete MOSFET model for analysis of digital and analog circuits,” *Comput. Des. Integr. Circuits Syst. IEEE Trans.*, vol. 15, no. 1, pp. 1–7, 1996.
 - [25] R. Van Langevelde and G. Gildenblat, “PSP: An advanced surface-potential-based MOSFET model,” in *Transistor Level Modeling For Analog/RF IC Design*, 2006, pp. 29–66.
 - [26] G. Gildenblat, H. Wang, T. L. Chen, X. Gu, and X. Cai, “SP: An advanced surface-potential-based compact MOSFET model,” in *IEEE Journal of Solid-State Circuits*, 2004, vol. 39, no. 9, pp. 1394–1406.
 - [27] X. Zhou *et al.*, “Unified Regional Charge-based Versus Surface-potential-based Compact Modeling Approaches,” *Tech. Proc. 2005 Work. Compact Model.*, vol. 2005, p. 6, 2005.
 - [28] J. M. Sallese, M. Bucher, F. Krummenacher, and P. Fazan, “Inversion charge linearization in MOSFET modeling and rigorous derivation of the EKV compact model,” *Solid. State. Electron.*, vol. 47, no. 4, pp. 677–683, 2003.
 - [29] C. C. Enz, “A Short Story of the EKV MOS Transistor Model,” *IEEE Solid-State Circuits Newsl.*, vol. 13, no. 3, pp. 24–30, 2008.
 - [30] “Anderson’s rule.” [Online]. Available: https://en.wikipedia.org/wiki/Anderson%27s_rule.
 - [31] S. C. Binari *et al.*, “Trapping effects and microwave power performance in AlGaIn/GaN HEMTs,” *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 465–471, 2001.
 - [32] J. Liu, Y. Zhou, J. Zhu, Y. Cai, K. M. Lau, and K. J. Chen, “DC and RF characteristics of AlGaIn/GaN/InGaIn/GaN double-heterojunction HEMTs,” *IEEE Trans. Electron Devices*, vol. 54, no. 1, pp. 2–10, 2007.
 - [33] K. Chandrasekaran, X. Zhou, S. Ben Chiah, W. Shangguan, and G. H. See, “Physics-based single-piece charge model for strained-Si MOSFETs,” *IEEE Trans. Electron Devices*, vol. 52, no. 7, pp. 1555–1562, 2005.
 - [34] X. Zhou, G. Zhu, G. H. See, K. Chandrasekaran, S. Ben Chiah, and K. Y. Lim, “Unification of MOS compact models with the unified regional modeling approach,” *J. Comput. Electron.*, vol. 10, no. 1–2, pp. 121–135, 2011.
 - [35] C. C. McAndrew, “Validation of MOSFET model Source Drain Symmetry,” *Electron Devices, IEEE Trans.*, vol. 53, no. 9, pp. 2202–2206, 2006.
 - [36] S. Helkman, S. Keller, Y. Wu, J. S. Speck, S. P. DenBaars, and U. K. Mishra, “Polarization effects in AlGaIn/GaN and GaIn/AlGaIn/GaN heterostructures,” *J. Appl. Phys.*, vol. 93, no. 12, pp. 10114–10118, 2003.

References

- [37] O. Ambacher *et al.*, “Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaIn/GaN heterostructures,” *J. Appl. Phys.*, vol. 85, no. 6, p. 3222, 1999.
- [38] Rashmi, A. Kranti, S. Haldar, and R. S. Gupta, “An accurate charge control model for spontaneous and piezoelectric polarization dependent two-dimensional electron gas sheet charge density of lattice-mismatched AlGaIn/GaN HEMTs,” *Solid. State. Electron.*, vol. 46, no. 5, pp. 621–630, 2002.
- [39] X. Cheng and Y. Wang, “A new analytical high frequency noise parameter model for AlGaIn/GaN HEMT,” *Solid. State. Electron.*, vol. 54, no. 11, pp. 1300–1303, 2010.
- [40] X. Cheng, M. Li, and Y. Wang, “An analytical model for current-voltage characteristics of AlGaIn/GaN HEMTs in presence of self-heating effect,” *Solid. State. Electron.*, vol. 54, no. 1, pp. 42–47, 2010.
- [41] A. Zhang *et al.*, “Analytical modeling of capacitances for GaN HEMTs, including parasitic components,” *IEEE Trans. Electron Devices*, vol. 61, no. 3, pp. 755–761, 2014.
- [42] M. Li and Y. Wang, “2-D Analytical Model for Current – Voltage Characteristics and Transconductance,” *IEEE Trans. Electron Devices*, vol. 55, no. 1, pp. 261–267, 2008.
- [43] X. Cheng, M. Li, and Y. Wang, “Physics-based compact model for AlGaIn/GaN MODFETs with close-formed I-V and C-V characteristics,” *IEEE Trans. Electron Devices*, vol. 56, no. 12, pp. 2881–2887, 2009.
- [44] X. Cheng and Y. Wang, “A surface-potential-based compact model for AlGaIn/GaN MODFETs,” *IEEE Trans. Electron Devices*, vol. 58, no. 2, pp. 448–454, 2011.
- [45] S. Khandelwal and T. A. Fjeldly, “A physics based compact model of I-V and C-V characteristics in AlGaIn/GaN HEMT devices,” *Solid. State. Electron.*, vol. 76, pp. 60–66, 2012.
- [46] S. Ghosh, A. Dasgupta, S. Khandelwal, S. Agnihotri, and Y. S. Chauhan, “Surface-potential-based compact modeling of gate current in AlGaIn/GaN HEMTs,” *IEEE Trans. Electron Devices*, vol. 62, no. 2, pp. 443–448, 2015.
- [47] S. Khandelwal, N. Goyal, and T. A. Fjeldly, “A physics-based analytical model for 2DEG charge density in AlGaIn/GaN HEMT devices,” *IEEE Trans. Electron Devices*, vol. 58, no. 10, pp. 3622–3625, 2011.
- [48] S. Khandelwal and T. A. Fjeldly, “A physics based compact model of gate capacitance in AlGaIn/GaN HEMT devices,” *2012 8th Int. Caribb. Conf. Devices, Circuits Syst. ICCDCS 2012*, vol. 1, no. 1, pp. 6–9, 2012.
- [49] X. Zhou, J. Zhang, B. Syamal, S. Ben Chiah, H. Zhou, and L. Yuan, “Unified regional modeling of GaN HEMTs with the 2DEG and DD formalism,” in *ICSICT 2012 - 2012 IEEE 11th International Conference on Solid-State and Integrated Circuit Technology, Proceedings*, 2012.
- [50] G. H. See *et al.*, “A compact model satisfying Gummel symmetry in higher order derivatives and applicable to asymmetric MOSFETs,” *IEEE Trans. Electron Devices*, vol. 55, no. 2, pp. 624–631, 2008.
- [51] N. Arora, *Mosfet modeling for VLSI simulation: theory and practice*. 2007.
- [52] A. Toriumi, M. Iwase, and H. Tango, “On the Universality of Inversion Layer Mobility in Si MOSFET’s: Part I—Effects of Substrate Impurity Concentration,” *IEEE Trans. Electron Devices*, vol. 41, no. 12, pp. 2357–2362, 1994.
- [53] K. Y. Lim and X. Zhou, “An analytical effective channel-length modulation

References

- model for velocity overshoot in submicron MOSFETs based on energy-balance formulation,” *Microelectron. Reliab.*, vol. 42, no. 12, pp. 1857–1864, 2002.
- [54] U. Radhakrishna, D. Piedra, Y. Zhang, T. Palacios, and D. Antoniadis, “High voltage GaN HEMT compact model: Experimental verification, field plate optimization and charge trapping,” *Tech. Dig. - Int. Electron Devices Meet. IEDM*, pp. 814–817, 2013.
 - [55] V. O. Turin and A. A. Balandin, “Electrothermal simulation of the self-heating effects in GaN-based field-effect transistors,” *J. Appl. Phys.*, vol. 100, no. 5, 2006.
 - [56] Y. Zhang *et al.*, “Electrothermal simulation and thermal performance study of GaN vertical and lateral power transistors,” *IEEE Trans. Electron Devices*, vol. 60, no. 7, pp. 2224–2230, 2013.
 - [57] M. Thorsell, K. Andersson, H. Hjelmgren, and N. Rorsman, “Electrothermal access resistance model for GaN-based HEMTs,” *IEEE Trans. Electron Devices*, vol. 58, no. 2, pp. 466–472, 2011.
 - [58] D. E. Ward and R. W. Dutton, “A charge-oriented model for MOS transistor capacitances,” *IEEE J. Solid-State Circuits*, vol. 13, no. 5, pp. 703–708, 1978.
 - [59] P. H. Woerlee, R. Van Langevelde, A. H. Montree, D. B. M. Klaassen, L. F. Tiemeijer, and P. W. H. De Vreede, “RF-CMOS performance trends,” in *European Solid-State Device Research Conference*, 2000, pp. 576–579.
 - [60] X. Zhou, J. Zhang, B. Syamal, Z. Zhu, H. Zhou, and S. B. Chiah, “Top-down drift-diffusion versus bottom-up quasi-ballistic formalism in device compact modeling,” in *Proceedings of the 20th International Conference on Mixed Design of Integrated Circuits and Systems, MIXDES 2013*, 2013, p. 53.
 - [61] V. Desmaris *et al.*, “Comparison of the DC and microwave performance of AlGaIn/GaN HEMTs grown on SiC by MOCVD with Fe-doped or unintentionally doped GaN buffer layers,” *IEEE Trans. Electron Devices*, vol. 53, no. 9, pp. 2413–2417, 2006.
 - [62] Y. C. Choi, L. F. Eastman, and M. Pophristic, “Effects of an Fe-doped GaN buffer in AlGaIn/GaN power HEMTs on Si substrate,” in *ESSDERC 2006 - Proceedings of the 36th European Solid-State Device Research Conference*, 2006, pp. 282–285.
 - [63] M. J. Uren *et al.*, “Intentionally carbon-doped algan/gan HEMTs: Necessity for vertical leakage paths,” *IEEE Electron Device Lett.*, vol. 35, no. 3, pp. 327–329, 2014.
 - [64] H. Tang, J. B. Webb, J. A. Bardwell, S. Raymond, J. Salzman, and C. Uzan-Saguy, “Properties of carbon-doped GaN,” *Appl. Phys. Lett.*, vol. 78, no. 6, pp. 757–759, 2001.
 - [65] U. Radhakrishna, L. Wei, D. S. Lee, T. Palacios, and D. Antoniadis, “Physics-based GaN HEMT transport and charge model: Experimental verification and performance projection,” in *Technical Digest - International Electron Devices Meeting, IEDM*, 2012.
 - [66] J. W. Chung, J. C. Roberts, E. L. Piner, and T. Palacios, “Effect of gate leakage in the subthreshold characteristics of AlGaIn/GaN HEMTs,” *IEEE Electron Device Lett.*, vol. 29, no. 11, pp. 1196–1198, 2008.
 - [67] D. M. Sathaiya and S. Karmalkar, “Thermionic trap-assisted tunneling model and its application to leakage current in nitrided oxides and AlGaIn/GaN high electron mobility transistors,” *J. Appl. Phys.*, vol. 99, no. 9, 2006.
 - [68] H. Kim, J. Lee, D. Liu, and W. Lu, “Gate current leakage and breakdown mechanism in unpassivated AlGaInGaN high electron mobility transistors by post-gate annealing,” *Appl. Phys. Lett.*, vol. 86, no. 14, pp. 1–3, 2005.

References

- [69] F. A. Padovani and R. Stratton, "Field and thermionic-field emission in schottky barriers," *Solid. State. Electron.*, vol. 9, pp. 695–707, 1966.
- [70] S. Turuvekere, N. Karumuri, A. A. Rahman, A. Bhattacharya, A. Dasgupta, and N. Dasgupta, "Gate leakage mechanisms in AlGa_N/Ga_N and AlIn_N/Ga_N HEMTs: Comparison and modeling," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3157–3165, 2013.
- [71] A. Goswami, R. J. Trew, and G. L. Bilbro, "Modeling of the gate leakage current in AlGa_N/Ga_N HFETs," *IEEE Trans. Electron Devices*, vol. 61, no. 4, pp. 1014–1021, 2014.
- [72] E. J. Miller, X. Z. Dang, and E. T. Yu, "Gate leakage current mechanisms in AlGa_N/Ga_N heterostructure field-effect transistors," *J. Appl. Phys.*, vol. 88, no. 10, p. 5951, 2000.
- [73] T. Hashizume, J. Kotani, and H. Hasegawa, "Leakage mechanism in Ga_N and AlGa_N Schottky interfaces," *Appl. Phys. Lett.*, vol. 84, no. 24, pp. 4884–4886, 2004.
- [74] O. Mitrofanov and M. Manfra, "Mechanisms of gate lag in Ga_N/AlGa_N/Ga_N high electron mobility transistors," *Superlattices Microstruct.*, vol. 34, no. 1–2, pp. 33–53, 2003.
- [75] W. Kruppa, S. C. Binari, and K. Doverspike, "Low-frequency dispersion characteristics of Ga_N HFETs," *Electron. Lett.*, vol. 31, no. 22, pp. 1951–1952, 1995.
- [76] E. Kohn, I. Daumiller, P. Schmid, N. X. Nguyen, and C. N. Nguyen, "Large signal frequency dispersion of AlGa_N Ga_N heterostructure field effect transistors," *Electron. Lett.*, vol. 35, no. 12, pp. 1022–1024, 1999.
- [77] G. Crupi *et al.*, "Ga_N HEMT large-signal model accounting for both low-frequency dispersion and high-frequency non-quasi-static effects," in *2011 10th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, TELSIKS 2011 - Proceedings of Papers*, 2011, pp. 234–237.
- [78] M. a. Khan, M. S. Shur, Q. C. Chen, and J. N. Kuznia, "Current/voltage characteristic collapse in AlGa_N/Ga_N heterostructure insulated gate field effect transistors at high drain bias," *Electron. Lett.*, vol. 30, no. 25, p. 2175, 1994.
- [79] J. F. J. P. B. Klein S. C. Binari, A. E. Wickenden, "Observation of deep traps responsible for current collapse in Ga_N metal-semiconductor field-effect transistors," *Appl. Phys. Lett.*, vol. 75, no. 25, pp. 4016–4018, 1999.
- [80] J. Joh and J. A. Alamo, "A Current-Transient Methodology for Trap Analysis for Ga_N High Electron Mobility Transistors," vol. 58, no. 1, pp. 132–140, 2011.
- [81] G. Meneghesso, F. Rampazzo, P. Kordo?, G. Verzellesi, and E. Zanoni, "Current collapse and high-electric-field reliability of unpassivated Ga_N/AlGa_N/Ga_N HEMTs," *IEEE Trans. Electron Devices*, vol. 53, no. 12, pp. 2932–2940, 2006.
- [82] W. Zhang *et al.*, "Influence of the Interface Acceptor-Like Traps on the Transient Response of AlGa_N / Ga_N HEMTs," *IEEE Electron Device Lett.*, vol. 34, no. 1, pp. 2012–2014, 2013.
- [83] J. K. Kaushik, V. R. Balakrishnan, B. S. Panwar, and R. Muralidharan, "Inverse temperature dependence of reverse gate leakage current in AlGa_N/Ga_N HEMT," *Semicond. Sci. Technol.*, vol. 28, no. 1, p. 15026, 2013.
- [84] D. Bisi *et al.*, "Deep-level characterization in Ga_N HEMTs-Part I: Advantages and limitations of drain current transient measurements," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3166–3175, 2013.
- [85] M. J. Anand, G. I. Ng, S. Arulkumaran, B. Syamal, and X. Zhou, "Distribution

References

- of trap energy level in AlGaIn/GaN high-electron-mobility transistors on Si under ON-state stress,” *Appl. Phys. Express*, vol. 8, no. 10, 2015.
- [86] B. Syamal *et al.*, “GaN HEMT compact model for circuit simulation,” *Proc. 2015 IEEE Int. Conf. Electron Devices Solid-State Circuits, EDSSC 2015*, pp. 535–538, 2015.
 - [87] B. Syamal, X. Zhou, S. B. Chiah, A. M. Jesudas, S. Arulkumaran, and G. I. Ng, “A comprehensive compact model for GaN HEMTs, including quasi-steady-state and transient trap-charge effects,” *IEEE Trans. Electron Devices*, vol. 63, no. 4, pp. 1478–1485, 2016.
 - [88] D. Kuzum, J. H. Park, T. Krishnamohan, H. S. P. Wong, and K. C. Saraswat, “The effect of donor/acceptor nature of interface traps on Ge MOSFET characteristics,” *IEEE Trans. Electron Devices*, vol. 58, no. 4, pp. 1015–1022, 2011.
 - [89] Y. Qiu, R. Wang, Q. Huang, and R. Huang, “A comparative study on the impacts of interface traps on tunneling FET and MOSFET,” *IEEE Trans. Electron Devices*, vol. 61, no. 5, pp. 1284–1291, 2014.
 - [90] A. Appaswamy, P. Chakraborty, and J. D. Cressler, “Influence of interface traps on the temperature sensitivity of MOSFET drain-current variations,” *IEEE Electron Device Lett.*, vol. 31, no. 5, pp. 387–389, 2010.
 - [91] A. Cester, L. Bandiera, S. Cimino, A. Paccagnella, and G. Ghidini, “Incidence of oxide and interface degradation on MOSFET performance,” in *Microelectronic Engineering*, 2004, vol. 72, no. 1–4, pp. 66–70.
 - [92] W. C. Kao, A. Ali, E. Hwang, S. Mookerjee, and S. Datta, “Effect of interface states on sub-threshold response of III-V MOSFETs, MOS HEMTs and tunnel FETs,” *Solid. State. Electron.*, vol. 54, no. 12, pp. 1665–1668, 2010.
 - [93] Z. Chen, X. Zhou, G. Zhu, and S. Lin, “Interface-trap modeling for silicon-nanowire MOSFETs,” *IEEE Int. Reliab. Phys. Symp. Proc.*, pp. 977–980, 2010.
 - [94] F. Najam *et al.*, “Interface trap density of gate-all-around silicon nanowire field-effect transistors with TiN gate: Extraction and compact model,” *IEEE Trans. Electron Devices*, vol. 60, no. 8, pp. 2457–2463, 2013.
 - [95] J. S. Blakemore, “Approximations for Fermi-Dirac integrals, especially the function $F_1(2)$ used to describe electron density in a semiconductor,” *Solid State Electronics*, vol. 25, no. 11, pp. 1067–1076, 1982.
 - [96] F. Principato, A. Caddemi, and G. Ferrante, “Experimental investigation of the kink effect and the low frequency noise properties in pseudomorphic HEMT’s,” *Solid. State. Electron.*, vol. 49, no. 6, pp. 915–922, 2005.
 - [97] M. Wang and K. J. Chen, “Kink effect in AlGaIn/GaN HEMTs induced by Drain and gate pumping,” *IEEE Electron Device Lett.*, vol. 32, no. 4, pp. 482–484, 2011.
 - [98] M.-Y. Cao *et al.*, “An improved EEHEMT model for kink effect on AlGaIn/GaN HEMT,” *Chinese Phys. B*, vol. 23, no. 8, p. 87201, 2014.
 - [99] N. Killat, M. J. Uren, D. J. Wallis, T. Martin, and M. Kuball, “Origin of kink effect in AlGaIn/GaN high electron mobility transistors: Yellow luminescence and Fe doping,” *Appl. Phys. Lett.*, vol. 101, no. 15, 2012.
 - [100] G. Meneghesso, F. Zanoni, M. J. Uren, and E. Zanoni, “Anomalous kink effect in GaN high electron mobility transistors,” *IEEE Electron Device Lett.*, vol. 30, no. 2, pp. 100–102, 2009.
 - [101] R. Cuervo *et al.*, “The Kink Effect at Cryogenic Temperatures in Deep Submicron AlGaIn / GaN HEMTs,” vol. 30, no. 3, pp. 209–212, 2009.
 - [102] E. H. Nicollian and A. Goetzberger, “The Si/SiO₂ Interface: Electrical Properties as Determined by the Metal-Insulator-Silicon Conductance

References

- Technique,” *Bell System Technical Journal*, vol. 46, no. 6, pp. 1055–1133, 1967.
- [103] K. Martens *et al.*, “On the correct extraction of interface trap density of MOS devices with high-mobility semiconductor substrates,” *IEEE Trans. Electron Devices*, vol. 55, no. 2, pp. 547–556, 2008.
 - [104] H. A. Shih, M. Kudo, and T. K. Suzuki, “Analysis of AlN/AlGaIn/GaN metal-insulator-semiconductor structure by using capacitance-frequency-temperature mapping,” *Appl. Phys. Lett.*, vol. 101, no. 4, pp. 3–7, 2012.
 - [105] M. Fagerlind *et al.*, “Investigation of the interface between silicon nitride passivations and AlGaIn/AlN/GaN heterostructures by C(V) characterization of metal-insulator-semiconductor-heterostructure capacitors,” *J. Appl. Phys.*, vol. 108, no. 1, 2010.
 - [106] Z. Chen, B. B. Jie, and C. T. Sah, “Effects of energy distribution of interface traps on recombination dc current-voltage line shape,” *J. Appl. Phys.*, vol. 100, no. 11, 2006.
 - [107] T. Kubota, “Estimation of Interface and Oxide Defects in Direct Contact High-k / Si Structure by Conductance Method,” 2011.
 - [108] M. apajna *et al.*, “Impact of GaN cap on charges in Al₂O₃/(GaN)/AlGaIn/GaN metal-oxide-semiconductor heterostructures analyzed by means of capacitance measurements and simulations,” *J. Appl. Phys.*, vol. 116, no. 10, 2014.
 - [109] H. Yang, Y. Son, S. Choi, and H. Hwang, “Improved conductance method for determining interface trap density of metal-oxide-semiconductor device with high series resistance,” *Japanese J. Appl. Physics, Part 2 Lett.*, vol. 44, no. 46–49, 2005.
 - [110] E. J. Miller *et al.*, “Trap characterization by gate-drain conductance and capacitance dispersion studies of an AlGaIn/GaN heterostructure field-effect transistor,” *J. Appl. Phys.*, vol. 87, no. 11, p. 8070, 2000.
 - [111] S. C. Binari, W. Kruppa, H. B. Dietrich, G. Kelner, A. E. Wickenden, and J. A. Freitas, “Fabrication and characterization of GaN FETs,” *Solid. State. Electron.*, vol. 41, no. 10, pp. 1549–1554, 1997.
 - [112] P. B. Klein *et al.*, “investigation of traps producing current collapse in AlGaIn/GaN high electron mobility transistors,” *Electron. Lett.*, vol. 37, no. 10, pp. 661–662, 2001.
 - [113] G. Meneghesso *et al.*, “Trapping phenomena in AlGaIn/GaN HEMTs: a study based on pulsed and transient measurements,” *Semicond. Sci. Technol.*, vol. 28, no. 7, p. 74021, 2013.
 - [114] D. Jin and J. A. Del Alamo, “Methodology for the study of dynamic ON-resistance in high-voltage GaN field-effect transistors,” *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3190–3196, 2013.
 - [115] W. D. Hu, X. S. Chen, and W. Lu, “Intrinsic mechanism of drain-lag and current collapse in GaN-based HEMTs,” *2009 IEEE Work. Microelectron. Electron Devices, WMED 2009*, no. d, pp. 35–37, 2009.
 - [116] W. D. Hu, X. S. Chen, Z. J. Quan, C. S. Xia, W. Lu, and H. J. Yuan, “Demonstration and dynamic analysis of trapping of hot electrons at gate edge model for current collapse and gate lag in GaN-based high-electron-mobility transistor including self-heating effect,” *Appl. Phys. Lett.*, vol. 89, no. 24, pp. 2004–2007, 2006.
 - [117] M. apajna, R. J. T. Simms, Y. Pei, U. K. Mishra, and M. Kuball, “Integrated optical and electrical analysis: Identifying location and properties of traps in AlGaIn/GaN HEMTs during electrical stress,” *IEEE Electron Device Lett.*, vol. 31, no. 7, pp. 662–664, 2010.

References

- [118] M. J. Anand, G. I. Ng, S. Arulkumaran, B. Syamal, and X. Zhou, "Distribution of trap energy level in AlGaIn/GaN high-electron-mobility transistors on Si under ON-state stress," *Appl. Phys. Express*, vol. 8, no. 10, 2015.
- [119] T. Mattila and R. Nieminen, "Ab initio study of oxygen point defects in GaAs, GaN, and AlN," *Phys. Rev. B*, vol. 54, no. 23, pp. 16676–16682, 1996.
- [120] M. Asghar, P. Muret, B. Beaumont, and P. Gibart, "Field dependent transformation of electron traps in GaN p–n diodes grown by metal–organic chemical vapour deposition," *Mater. Sci. Eng. B*, vol. 113, no. 3, pp. 248–252, 2004.
- [121] A. Koudymov, M. S. Shur, G. Simin, and R. Gaska, "Current collapse and reliability of III–N heterostructure field effect transistors," *Phys. Status Solidi - Rapid Res. Lett.*, vol. 1, no. 3, pp. 116–118, 2007.
- [122] J. Scott, J. G. Rathmell, A. Parker, and M. Sayed, "Pulsed device measurements and applications," *IEEE Trans. Microw. Theory Tech.*, vol. 44, no. 12 PART 2, pp. 2718–2723, 1996.
- [123] K. Horio, K. Itagaki, and A. Nakajima, "Analysis of pulsed I–V curves and power slump in field-plate GaN-based FETs," *2008 Int. Conf. Microw. Millim. Wave Technol. Proceedings, ICMMT*, vol. 2, pp. 893–896, 2008.
- [124] A. Chini, M. Esposto, G. Meneghesso, and E. Zanoni, "Evaluation of GaN HEMT degradation by means of pulsed I–V, leakage and DLTS measurements," *Electron. Lett.*, vol. 45, no. 8, p. 426, 2009.
- [125] M. Gassoumi, B. Grimbert, C. Gaquiere, and H. Maaref, "Evidence of surface states for AlGaIn / GaN / SiC HEMTs passivated Si₃N₄ by CDLTS," pp. 396–399, 2012.
- [126] J. G. Simmons, "Poole-Frenkel effect and Schottky effect in metal-insulator-metal systems," *Phys. Rev.*, vol. 155, no. 3, pp. 657–660, 1967.
- [127] P. K. Rao, B. Park, S. T. Lee, Y. K. Noh, M. D. Kim, and J. E. Oh, "Analysis of leakage current mechanisms in Pt/Au Schottky contact on Ga-polarity GaN by Frenkel-Poole emission and deep level studies," *J. Appl. Phys.*, vol. 110, no. 1, pp. 2–7, 2011.
- [128] R. Ongaro and A. Pillonnet, "Poole-Frenkel (PF) effect high field saturation," *Rev. Phys. Appliquée*, vol. 24, no. 12, pp. 1085–1095, 1989.
- [129] S. Ganichev, E. Ziemann, W. Prettl, I. Yassievich, a. Istratov, and E. Weber, "Distinction between the Poole-Frenkel and tunneling models of electric-field-stimulated carrier emission from deep levels in semiconductors," *Phys. Rev. B*, vol. 61, no. 15, pp. 10361–10365, 2000.
- [130] R. Vetury, N. Q. Zhang, S. Keller, and U. K. Mishra, "The impact of surface states on the DC and RF characteristics of AlGaIn/GaN HFETs," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 560–566, 2001.
- [131] G. Simin *et al.*, "Induced strain mechanism of current collapse in AlGaIn/GaN heterostructure field-effect transistors," *Appl. Phys. Lett.*, vol. 79, no. 16, pp. 2651–2653, 2001.
- [132] N. Braga, R. Mickevicius, R. Gaska, M. S. Shur, M. Asif Khan, and G. Simin, "Simulation of gate lag and current collapse in gallium nitride field-effect transistors," *Appl. Phys. Lett.*, vol. 85, no. 20, pp. 4780–4782, 2004.
- [133] N. Braga, R. Mickevicius, R. Gaska, M. S. Shur, M. A. Khan, and G. Simin, "Edge trapping mechanism of current collapse in III–N FETs," *IEEE Int. Electron Devices Meet.*, pp. 815–818, 2004.
- [134] S. Dasgupta *et al.*, "Slow detrapping transients due to gate and drain bias stress in high breakdown voltage AlGaIn/GaN HEMTs," *IEEE Trans. Electron Devices*, vol. 59, no. 8, pp. 2115–2122, 2012.

References

- [135] C. K. Williams, “Kinetics of trapping, detrapping, and trap generation,” *J. Electron. Mater.*, vol. 21, no. 7, pp. 711–720, 1992.
- [136] and J. C. M. H. Robert E. Leoni, III, Mikhail S. Shirokov, Jianwen Bao, “A phenomenologically based transient SPICE model for digitally modulated RF performance characteristics of GaAs MESFETs,” *IEEE Trans. Electron Devices*, vol. 49, no. 6, pp. 1680–1681, 2001.
- [137] J. B. King and T. J. Brazil, “Equivalent circuit GaN HEMT model accounting for gate-lag and drain-lag transient effects,” *RWW 2012 - Proc. 2012 IEEE Top. Conf. Power Amplifiers Wirel. Radio Appl. PAWR 2012*, pp. 93–96, 2012.
- [138] P. C. Canfield, S. C. F. Lam, and D. J. Allstot, “Modeling of frequency and temperature effects in GaAs MESFETs,” *IEEE J. Solid-State Circuits*, vol. 25, no. 1, pp. 299–306, 1990.