Charakterisierung und Modellierung von Aluminium–Galliumnitrid/Galliumnitrid–Heterostrukturfeldeffekttransistoren

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Abkürzungen

ADS	***A***dvanced ***D***esign ***S***ystem
2DEG	Two ***D***imensional ***E***lectron ***G***as
CW	***C***ontinuous ***W***ave
DC	***D***irect ***C***urrent
DGL	***D***ämpfungs***gl***ied
ECR–RIE	***E***lectron ***C***yclotron ***R***esonance – ***R***eactive ***I***on ***E***tch
ESB	***E***rsatz***s***chalt***b***ild
FET	***F***ield ***E***ffect ***T***ransistor
FOM	***F***igure ***o***f ***M***erit
GaAs	***Ga***llium***a***r***s***enid
GaN	***Ga***llium***n***itrid
GSG	***G***round ***S***ignal ***G***round
HBT	***H***eterojunction ***B***ipolar ***T***ransistor
HEMT	***H***igh ***E***lectron ***M***obility ***T***ransistor
HF	***H***och***f***requenz
HFET	***H***eterostructure ***F***ield ***E***ffect ***T***ransistor
JFM	***J***ohnson's ***F***igure of ***M***erit
IAF	***I***nstitut für ***A***ngewandte ***F***estkörperphysik
IMD	***I***nter***m***odulation ***D***istortions
InP	***In***dium***p***hosphid
LDMOS	***L***ateral ***D***ouble–Diffused ***M***etal ***O***xide ***S***emiconductor
LRRM	***L***ine – ***R***eflection – ***R***eflection – ***M***atch Kalibrationsverfahren
SOLT	***S***hort – ***O***pen – ***L***oad – ***T***hru Kalibrationsverfahren
NWA	***N***etz***w***erk – ***A***nalysator
MBE	***M***olecular ***B***eam ***E***pitaxy
MESFET	***Me***tal ***S***emiconductor ***F***ield ***E***ffect ***T***ransistor
MOCVD	***M***etal***o***rganic ***C***hemical ***V***apour ***D***eposition
MTA	***M***icrowave ***T***ransition ***A***nalyser
PAE	***P***ower ***A***dded ***E***fficiency
RT	***R***aum***t***emperatur
SDD	***S***ymbolically ***D***efined ***D***evice
Si	***Si***lizium
SiC	***Si***lizium***c***arbid
TLM	***T***ransmission ***L***ine ***M***odel

Symbolverzeichnis

Variable	***Einheit***	***Beschreibung***
a	m	Gitterkonstante
A	m^2	Fläche eines Bauelements
$\underline{a}_i$	V	Hinlaufende Welle am Tor i
B	1/m	Geometrischer Koeffizient
$\underline{b}_i$	V	Zurücklaufende Welle am Tor i
$C_{coupled}$	F/m	Längenbezogene Kapazität einer gekoppelten Mikrostreifenleitung im Gleichtaktbetrieb
C_f	F/m	Externe Randkapazität
C_{fe}	F/m	Interne Randkapazität
C_g	F	Gate–Kapazität
C_{gs0}, C_{gd0}	F	Gate–Source– und Gate–Drain–Kapazität im Abschnürbereich
C_{gs}, C_{gd}	F	Gate–Source– und Gate–Drain–Kapazität
C_j	F	Verteilte Schottky–Kapazität
C_{mikro}	F/m	Längenbezogene Kapazität einer Mikrostreifenleitung
C_p	F/m	Längenbezogene Kapazität eines Plattenkondensators
C_{pds}, C_{pgs}, C_{pgd}	F	Drain–Source–, Gate–Source– und Gate–Drain–Padkapazität
C_{th}	$W \cdot s/K$	Thermische Kapazität
D, D_i	–	Drain–Anschluss, intrinsischer Drain–Anschluss
d_i	m	Dicke der undotierten AlGaAs–Schicht
E_C, E_V	eV	Leitungs– bzw. Valenzbandenergie
ΔE_C, ΔE_V	eV	Diskontinuität des Leitungs– bzw. Valenzbandes
e_{ij}	–	Fehlermatrixkoeffizienten
E_0, E_1	eV	Quantisierte Energie
E_F	eV	Fermi–Niveau
E_g	eV	Bandlückenenergie
E_{krit}	V/m	Durchbruchfeldstärke
E_{pol}	V/m	Piezoelektrisches Feld
F	m	Substratdicke
Δf	Hz	Frequenzversatz
f_0	Hz	Frequenz der Grundwelle
F_{DC}	–	Relativer Fehler des Drain–Source–Stromes
F_{ij}	–	Relativer Fehler der S–Parameter
f_t	Hz	Transitfrequenz
G, G_i	–	Gate–Anschluss, intrinsischer Gate–Anschluss

Variable	***Einheit***	***Beschreibung***
GD	m	Abstand zwischen Gate– und Drain–Elektroden
g_{ds}	S	Ausgangsleitwert
g_m	S	Steilheit
$\underline{I}(k)$	A	Komplexe Amplitude des Stromes der k–ten Harmonischen
$i(t)$	A	Strom im Zeitbereich
I_{DC}	A	Gleichanteil des Stromes
I_{ds}	A	Drain–Source–Strom
I_{max}	A	Maximaler Drain–Source–Strom
$I_{ds,\ max}$	A/mm	Maximaler auf die Gate–Weite bezogener Drain-Source-Strom
I_{gs}	A	Gate–Source–Strom
I_{gd}	A	Gate–Drain–Strom
I_{th}	W	Thermische Stromquelle
J	A/m^2	Stromdichte
k	–	Ordnung der Harmonischen
$K(p)$	–	Vollständiges elliptisches Integral erster Art
L_G	m	Gate–Länge
L_{G-S}	m	Gate–Source–Abstand
L_{G-D}	m	Gate–Drain–Abstand
L_{tr}	m	Transferlänge des TLM–Kontakts
L_s, L_d, L_g	H	Source–, Drain– und Gate– Induktivität
L_{Kont}	m	Länge der TLM–Kontaktfläche
l_n	m	Abstand zwischen zwei TLM–Strukturen
n	–	Idealitätsfaktor
N	m^{-3}	Dotierungskonzentration
n_s	m^{-2}	Schichtladungsträgerkonzentration
P'	W/m^2	Flächenbezogene Verlustleistung
P_{DC}	W	Gleichanteil der Leistung
P_{diss}	W	Verlustleistung
P_{in}	W	Eingangsleistung
$P_{in,\ deliv}$	W	Aufgenommene Eingangsleistung
P_{max}	W	Maximale Leistung eines Bauelements
P_{out}	W/mm	Ausgangsleistung bezogen auf die Gate–Weite
Q_g	C	Gate–Ladung
Q_{gd}	C	Gate–Drain–Ladung
Q_{gs}	C	Gate–Source–Ladung
R	Ω	Realteil der komplexen Impedanz
R_C	Ω·mm	Kontaktwiderstand
R_{ch}	Ω	Kanalwiderstand
R_j	Ω	Differentieller Widerstand der Schottky–Diode
R_{fd}	Ω	Rückkopplungswiderstand zwischen Drain und Gate
R_{fs}	Ω	Rückkopplungswiderstand zwischen Source und Gate
R_{gs}	Ω	Gate–Source–Widerstand

Variable	***Einheit***	***Beschreibung***
R_{gd}	Ω	Gate–Drain–Widerstand
R_s, R_d, R_g	Ω	Source–, Drain– und Gate– Widerstand
R_{sh}	Ω/□	Schichtwiderstand
R_{th}	K/ W	Temperaturwiderstand
$R_{tot,\,n}$	Ω·mm	Widerstand zwischen zwei TLM–Kontakten
S	m	Abstand zwischen den Steuerelektroden des Multifingertransistors
S, $\mathrm{S_i}$	–	Source–Anschluss, intrinsischer Source–Anschluss
T	K	Temperatur
T_0	K	Bezugstemperatur in den Modellgleichungen
ΔT	K	Temperaturerhöhung
TK_h	**H**/K	Temperaturkoeffizient des Parameters h, wobei **H** die Einheit des Parameters h ist
U	V	Angelegte Spannung
$\underline{U}\,(k)$	V	Komplexe Amplitude der Spannung der k–ten Harmonischen
$u\,(t)$	V	Spannung in Zeitbereich
U_{br}	V	Durchbruchspannung
U_{bi}	V	Eingebaute Spannung
U_{DC}	V	Gleichanteil der Spannung
U_{ds}	V	Drain–Source–Spannung
U_{gs}	V	Gate–Source–Spannung
U_{dsi}	V	Innere Drain–Source–Spannung
U_{gsi}	V	Innere Gate–Source–Spannung
U_{knee}	V	Knie–Spannung
U_{th}	V	Schwellenspannung
v_{sat}	m/s	Elektronensättigungsgeschwindigkeit
W	m	Weite der Mesa in den TLM–Strukturen
W_f	m	Weite des Gate–Fingers
W_g	m	Gate–Weite
x	–	Al–Gehalt in $\mathrm{Al_xGa_{1-x}N}$
X	Ω	Imaginärteil der komplexen Impedanz
X_C	Ω	Kapazitiver Ausgangswiderstand
y_1, y_2	m	Weite der Raumladungszone im Material 1 bzw. 2
$[\underline{Y}_{in}]$	Ω^{-1}	Y–Parameter des intrinsischen Transistors
$[\underline{Y}_{mes}]$	Ω^{-1}	Gemessene Y–Parameter
$[\underline{Y}_p]$	Ω^{-1}	Admittanzmatrix des parallelen, parasitären Netzwerkes
$[\underline{Z}_s]$	Ω	Impedanzmatrix des seriellen, parasitären Netzwerkes
Z_0	Ω	Systemimpedanz

Griechische Buchstaben

Variable	Einheit	Beschreibung
α	rad	Wärmestreuungswinkel
ϵ	–	Relative Dielektrizitätskonstante
θ	K	Linearisierte Temperatur
λ	$\mathrm{W/(m \cdot K)}$	Wärmeleitfähigkeit
μ_n	$\mathrm{m^2/(V \cdot s)}$	Elektronenbeweglichkeit
ρ_C	$\Omega \cdot \mathrm{m}^2$	Spezifischer Kontaktwiderstand
σ	$\Omega^{-1}\mathrm{m}^{-2}$	Flächenbezogene elektrische Leitfähigkeit
σ_{PZ}	$\mathrm{C/m^2}$	Polarisationsladungsdichte
$\sigma_{surface}$	$\mathrm{C/m^2}$	Oberflächenladungsdichte
τ	s	Zeitkonstante
X	eV	Elektronenaffinität
Φ	eV	Austrittsarbeit
ω	Hz·rad	Kreisfrequenz
ω_0	Hz·rad	Kreisfrequenz der ersten Harmonischen
φ	rad	Phase

Physikalische Konstanten

$k = 1,38066 \cdot 10^{-23}$ J/K Boltzmann–Konstante

$q = 1,60218 \cdot 10^{-19}$ C Elementarladung

$\epsilon_0 = 8,85418 \cdot 10^{-12}$ F/m Dielektrische Konstante im Vakuum

$m_0 = 0,91094 \cdot 10^{-30}$ kg Elektronenmasse

Abstract

The revolutionary changes in the electronic industry came along with the invention of the transistor in the middle of the 20^{th} century. The first integrated circuits fostered the development of Silicon technology and made it the most reliable one. High frequency applications were enabled by GaAs-technology and the invention of the high electron mobility transistor. Third generation wireless systems with high frequency and high power signals brought new technological challenges. These two partly contradictory demands on power and frequency require new technological approaches. Only wide-bandgap semiconductor materials with a high critical field such as diamond, SiC or GaN can handle the requested powers and temperatures at microwave frequencies.

Although the first studies of wide-bandgap materials go back to the 60s, the material quality at that time was not sufficient for the needs of the semiconductor industry. High defect densities in the material, the lack of high-quality substrates and troubles with the doping prevented device processing. The last technological breakthroughs led to the development of extraordinary devices: blue lasers, high-power switches, rectifiers and microwave transistors.

Despite the obvious progress in wide-bandgap material technology a lot of unsolved problems persist. Diamond as a material with the best thermal conductivity still cannot be properly doped. SiC-transistors exhibit limited transit frequencies, which restrict the number of potential applications. The wide bandgap, the high saturation velocity of GaN and the high electron density in the transistor channel made GaN heterojunction transistors promising candidates for microwave high-power electronics. The best transistors achieve 12 W/mm at 10 GHz [1], 10 W/mm at 40 GHz [2] or 0.5 W/mm at 60 GHz [3].

Bulk GaN substrates are not yet available for the epitaxial growth of GaN and AlGaN layers. Therefore, sapphire, SiC or Si are used as substrate materials. The lattice mismatch between GaN and these substrate materials is up to 14 %, which results in a high defect density of the GaN layer. SiC has the best thermal conductivity among these materials and hence, is the most suitable substrate for transistors with high dissipated power. Since SiC substrates

are available only in small diameters and at high cost, sapphire substrates are often used. The poor thermal conductivity of sapphire limits the maximum current sustained by the AlGaN/GaN heterojunction. Silicon substrates offer a compromise between low cost and high thermal conductivity. However, much effort is still needed to overcome the parasitic coupling of the Silicon substrate at high frequencies.

AlGaN/GaN high electron mobility transistors (HEMTs) are grown on sapphire substrates by the 4^{th} Physical Institute, Universität Stuttgart. To overcome the lattice mismatch a nucleation layer of AlN is deposited on the substrate prior to the 1 μm GaN layer. To form the heterojunction with the two-dimensional electron gas a 30 nm AlGaN-layer with an Al content of 30% is grown. Finally, a 3.5 nm GaN layer is deposited to improve the contact resistance. The contact resistance evaluated with the transmission line model (TLM) is 0.6 – 0.8 Ω·mm, which is comparable with literature values.

The band discontinuities between AlGaN and GaN and the high piezoelectric field in the AlGaN layer result in a two dimensional electron gas (2DEG) at the AlGaN/GaN interface. In contrast to an AlGaAs/GaAs heterojunction the 2DEG is created even without an additional doping of the AlGaN layer. The electron concentration in the transistor channel is controlled by the potential of the gate electrode.

The DC output characteristics of the AlGaN/GaN HEMTs have a negative slope in the saturation region typical for high power transistors. At high voltages the dissipated power heats the transistor channel, which reduces the drain current. This self-heating effect is more pronounced if the thermal conductivity of the substrate is poor, and thus is an important feature of the model presented in this work. The maximum drain current normalised to the gate width is often compared to assess the quality of low power transistors. However, the power dissipation of power transistors makes this comparison inadequate, since self-heating is more important in transistors with larger gate widths.

The combination of a high maximum current and a high breakdown voltage in AlGaN/GaN HEMTs suggests a high RF output power. However, the measured RF power is often smaller than expected from the DC measurements. In the literature this effect is known as „power collapse“. Different approaches have been proposed to explain this discrepancy. The lattice mismatch between GaN and the substrate creates traps in the GaN buffer layer that can capture electrons and reduce the drain current. The surface of the AlGaN layer is very sensitive to small potential fluctuations. A „virtual“ gate can arise on the surface. This negatively charged gate decreases the drain current. A passivation layer has been reported to prevent the formation of the „virtual“ gate and hence the current degradation, but can increase the gate leakage current, if its quality is poor.

S-parameter measurements from 100 MHz to 40 GHz at different operating points are used to analyse the RF properties of the investigated AlGaN/GaN HEMTs. A physically motivated transistor small-signal equivalent circuit has been used in this work to assess the device performance and to improve the technology. Parasitic and internal equivalent circuit elements can be separately deduced from measurements at different dedicated operating points. A special routine for the automatic extraction of the gate parasitics has been developed, which is necessary if the gate resistance is large. The small-signal equivalent circuit for multiple operating points comprises the bias dependence of the nonlinear elements, which can be used later on for large-signal modelling.

Successful circuit design requires stable, precise and compact device models, which are suitable for large-signal simulation. A model based on an equivalent circuit appears to be the best approach for circuit design. Several authors have already published some modeling results on AlGaN/GaN HEMTs [4]–[7]. Most models have been designed for transistors on a substrate with good thermal conductivity such as SiC or Si, where the thermal effects are less pronounced than in devices on sapphire substrates. However, sapphire substrates are still commonly used, since they are available with larger wafer diameters and at lower cost. In contrast to the previous work our large-signal model includes thermal effects from self- and ambient heating. Most importantly, e.g. for the design of highly linear amplifiers, it accurately reflects the transistor's nonlinear behaviour, which produces harmonics and intermodulation distortion. Very often, the nonlinearity is described by polynomial functions, which achieve a good fit to the measured data within a selected region, but diverge outside. Since our model does not use polynomials, it yields realistic values and robust convergence.

The large-signal equivalent circuit of the AlGaN/GaN HEMTs presented here comprises an electrical and a thermal circuit. The electrical circuit is derived from the small-signal equivalent circuit. The parasitic elements are voltage and frequency independent, whereas the gate-source, gate-drain capacitances and drain-source current source depend on the operating voltages. The gate leakage currents are modelled with current sources governed by the Shockley equation. An additional thermal network describes the self-heating effect in the channel. It comprises the current source corresponding to the dissipated power, the thermal resistance and the thermal capacitance. The voltage drop on the thermal resistance gives the temperature rise in the channel. The thermal capacitance models the temperature based dispersion. The temperature rise gives feedback to the drain-source current. The temperature dependence of the drain current and parasitic resistances accurately reproduces the measured data at different temperatures.

The thermal resistance is calculated analytically, which allows to evaluate the channel temperature and to optimise the transistor layout for heat removal. The heat equation is analytically solved using conformal mapping techniques and the approximation of a constant heat spreading angle. The temperature dependence of the thermal conductivity is taken into account with a Kirchhoff transformation. As an example the isothermal lines for a two-finger transistor are given.

The model has the important advantage over other approaches, that all model parameters can be directly extracted from the measured data, which significantly improves the convergence of a subsequent numerical optimisation of the parameter set and furthermore allows for an automatic procedure.

Model verification is performed under DC, small-signal and large-signal excitation in order to verify the model under realistic conditions. Harmonic and intermodulation distortion measurements are in good agreement with simulation data indicating the quality of the model. Since the model equations and their voltage derivatives are continuous, the simulations are stable even in the highly nonlinear regions.

The model is implemented as a symbolically defined device in the Advanced Design System circuit simulator by Agilent Technologies, which is the standard software tool in the RF industry. The model is available as a component of a design kit library and thus is ready for use in circuit design.

In the future GaN-technology must be further improved to provide reproducible, stable and reliable transistors. If the devices have achieved application-grade quality the model for AlGaN/GaN HEMTs should be enhanced to cover the noise behaviour. The use and verification of the model for integrated circuit design will be the next step in the model development.