Chapter 1

Introduction

Gallium Nitride high electron mobility transistors (HEMT) utilize high-density two-dimensional electron gas (2DEG) accumulated in the boundary layer between GaN and AlGaN through their piezoelectric effect and natural polarization effect [1]. This makes it possible to realize a high current density and a high saturation voltage as its main transistor characteristics. Combined with its other characteristics, such as high power, low noise, and a high breakdown voltage, those outstanding characteristics make it ideal for high-power, high-frequency, low noise applications [2–4], e.g., in high-power amplifiers and LNA [5–9]. Furthermore, GaN HEMT has also shown great potential in extreme operation environments, e.g., high/low temperature operation conditions, which actually have a strong impact on the electrical performance of devices [10, 11]. Hence, despite that the technology of GaN HEMT is not as well understood as the previously adopted devices, e.g., GaAs HEMT, the development of its commercial production never stopped.

However, this puts the circuit designers in a very awkward position: on one hand, they are attracted to the outstanding characteristics of GaN HEMTs, and many of them actually have already benefited from the use of GaN HEMTs in their designs. On the other hand, the demand for accurate GaN HEMT models is still pressing, as they are still not fast enough to be used in most circuit simulators.

During the past years, many large-signal models for GaN HEMTs in different types were developed to characterize their large-signal behavior [12–15]. However, high modeling accuracy can be considered to be quite close to be guaranteed in the academic world, but still far away from being accessible to circuit designers. This is mainly due to the anomalies of GaN HEMTs caused by dispersion effects [16–18], which are still the key issues in the modeling community.

In the following, different types of large-signal models will be first discussed and compared. Next, the challenges of the GaN HEMT modeling will be presented in detail. Finally, a brief review of the whole work will be addressed.

1.1 Large-Signal Model Types

Large signal models normally fall into two main types:

1. Physical models
   These models use the parameters based upon device properties, such as gate width, gate length, and thickness of layers, or upon physical data, such as carrier transport properties and the device geometry, in order to solve physics equations that describe the device characteristics, e.g., current, voltage, power, etc [19–23].

2. Empirical models
   This type of model is entirely based upon curve fitting. This means the parameters of these models are normally determined by fitting the equations to the measured data through mathematical optimization.

Considering the shortcomings of traditional empirical model, such as non-physical nature and too many fitting parameters, which are often difficult to be understood and extracted, physical models show their advantages due to its inherent superiority such as explicit physical implication and unified expression to describe all the regions of device operation [24–27].

Compared with physical models, the empirical large-signal equivalent circuit model is simpler and easier to be implemented in commercial simulators and has been widely used in circuit design [28]. Basically, the nonlinear empirical models are generated with nonlinear functions that could account for the current flow (I/V functions) and the charge dynamic variation. They are also able to describe the device physical phenomena as long as the model parameters are linked to physical effects. However, the modeling accuracy strongly depends on the accuracy of the measurements, and the adequacy of the model formulation. Moreover, these models can also be constructed based upon a lookup table developed from the measured data, and therefore are called “table-based models” [29–31]. Moreover, recently, a new type of empirical models has been presented, which utilizes artificial neural network, or AAN [32–35].

In this work, a well known empirical model, i.e., the Chalmers (Angelov) nonlinear model [36], has been adopted, as it is one of the frequently used GaN HEMT models. Its parameter extraction techniques have been already researched and developed in the last years [37–39], e.g., its drain current model's parameters can be directly extracted by simple inspection of the experimental DC I/V and g_m characteristics, in this way. the model can accurately predict not only I_{ds} but also its derivatives. However, for GaN HEMTs, the drain current model is more complex than that for Si or GaAs devices [36], since the model should also include the functions to account for the trapping effects that GaN HEMTs encounter under working conditions. The details will be addressed in next section.

1.2 GaN HEMT Modeling Challenges

As mentioned previously, GaN HEMT offer outstanding characteristics, that attracts more and more circuit designers. However, at the same time, its models suffer from the electrical anomalies of the GaN HEMT induced by the trapping effects. The trapping effects can normally be split into two groups: drain-lag effects are caused by the charge capture and emission processes of the donor traps in the buffer layers below the 2DEG and gate-lag effects are mainly due to the presence of negative charges trapped on the semiconductor surfaces of the epitaxial layers above the 2DEG [40]. Gate-lag effects in recent AlGaN/GaN technology have been significantly reduced by passivation and field plate. For some devices, e.g., in our case, gate-lag effects are so weak, that it is almost impossible to distinguish between gate-lag effects and thermal effects even by means of pulsed measurements [41]. Hence, drain-lag effects remain the main trap phenomena. Since static DC I/V measurements without separating trapping effects can lead to inaccurate RF models [42],[43], it is important to include these effects in the transistor large-signal models to describe the transistor's RF behavior accurately.

From a view of DC/pulsed I/V characteristic prediction, a drain-lag model worth its salt would have the following abilities: First, it should be able to describe the drain-source current slump, which is known as the knee-walkout [17]. Furthermore, the typical kink observed in pulsed I/V curves should also be described, which is mainly due to the asymmetry in time constants associated with capture and release of charge traps [44].

On the other hand, it is reported that the transconductance dispersion is mainly related to gate-lag effects [45], while output conductance dispersion is mainly related to the drain-lag effects [46]. Hence, the drain-lag model is also supposed to be able to provide a correction term ΔG_{ds} to account for the difference between the output conductance G_{ds} extracted from small-signal RF characteristics ($G_{ds,RF}$) and that obtained from DC I/V characteristics ($G_{ds,DC}$) [47]. The use of the drain-lag model without this correction term could result in a mismatch in predicting the real part of S_{22}, which is basically influenced by the output conductance G_{ds}.

In the last decade, a significant interest on modeling drain-lag effects can be observed within the microwave community. As a result, various trap models [47–52] have been published. However, until now, none of them was available in commercial EDA tools. There are two main reasons here: on the one hand, some models are of little use to describe some impacts of drain-lag effects, e.g., Jarndal et al. [47] proposed a drain-lag model which cannot account for the difference between emission and capture time constants. On the other hand, some drain-lag models are most accurate since they are able to fully predict the impact of trapping effects on nonlinear device performance. However, the parameters of these models have proven to be too complicated to be extracted, e.g., Jardel and Quéré et al. [44, 48] developed a drain-lag model (in this work it is called Quéré drain-lag model), but no publication so far exactly addresses the question how to describe the values of the trap-related parameter k employed in this drain-lag model, as it is only assumed to be a linear function of v_{gs} for reasons of simplicity in [44, 48].

In this work, first of all, a simple drain-lag model, named parameter-scaling drain-lag model [49], is proposed. This drain-lag model is able to predict device performance well for various trap states. It relies on scaling of model parameters with quiescent drain voltage which yields convenient parameter extraction. Another benefit of this model is that it reduces to the standard Chalmers model with optimized parameters for fixed drain bias. However, it is of little use in describing the typical kink around the quiescent drain voltage from pulsed I/V curves or predicting the RF output conductance under large-signal condition. Thus, the Quéré drain-lag model was integrated to overcome these drawbacks. This drain-lag model employs a pseudo gate-source voltage at the input of the current source. The pseudo gate-source voltage is related to a fitting parameter k, which is linked to the amplitude of traps and is assumed to be a linear function of v_{gs}. However, it is shown that, instead of the complicated expression of parameter k as presented in Quéré drain-lag model, a constant value should yield the same modeling performance if combined with the parameter-scaling drain-lag model. This can significantly simplify the model parameters extraction process.

1.3 Outline of the Thesis

This thesis is structured as follows:

Chapter 1 describes the objective of this thesis and the motivation behind performing this research. The state of art of the GaN HEMT trap models is briefly reviewed and the associated problems due to their inaccuracy and complexity are summarized.

In **Chpater 2**, at first, a brief overview of the structure and operation of AlGaN/GaN HEMT is given in order to provide the physical background of the main behaviors to be modeled. Next, a detailed description of the proposed GaN HEMT modeling strategy is presented. Finally, the physical mechanisms of the trapping effects are introduced, and the advantages and drawbacks of the published trap models are clarified.

Chapter 3 presents the principle and set up of the used multi-bias pulsed S-parameter measurements. Moreover, the main characteristics of pulsed measurements are discussed.

The GaN HEMT modeling relying on the pulsed S-parameter measurements is covered in **Chapter 4**. The impact of the use of the pulsed S-parameter measurements on the extraction of extrinsic parameters and intrinsic capacitances of small-signal model is presented in the first section of this chapter. The second part shows that better large-signal models can be extracted by using the multi-bias pulsed S-parameter measurements.

Chapter 5 addresses a novel drain-lag model to account for trapping effects in the large-signal description of GaN HEMTs. The model formulations are presented and reasoned, and the methods to determine the model parameters are explained. However, significant discrepancies are observed when verifying the model with pulsed S-parameters. The reason for this drawback is discussed in detail at the end of the chapter.

A solution to overcome this drawback is presented in **Chapter 6**. The modeling accuracy and the reliability of the extraction results are verified by comparison of small- and large-signal simulations with measurement data.

General conclusions and required improvements in future work are discussed in **Chapter 7**.

Chapter 2

GaN HEMT Modeling Strategy

The significant progress made on technology of GaN HEMTs for the last years makes them usable in many different areas where e.g., high power and high frequency are needed, and they seem to be able to replace several existing semiconductor technologies, e.g., GaAs, Si, and SiC devices, in these areas [53]. With this rapid development a need of accurate large-signal models for GaN HEMT is pressing, since these models are the key elements to simulate the circuits in commercial EDA tools.

In Section 1, the fundamentals of technology, structure, and basic operation of GaN HEMTs will be discussed in detail. This background information is very important for the accurate device modeling.

The proposed modeling strategy in this thesis can be split in two stages: small- and large- signal modeling. Section 2 introduces the extraction process of the small-signal equivalent circuit parameters, which has become well published for HEMTs or FETs in some references [54–56].

Section 3 will address the next issue after small-signal modeling: Large-signal modeling. The Chalmers (Angelov) model [36–39] was applied here, as it is a frequently used and well-known GaN HEMT model.

Section 4 discusses the state-of-the-art dispersive effect modeling strategy of GaN HEMTs. As mentioned in Chapter 1, dispersion effects, also known as memory effects, not only hamper the achievable output power and linearity of HEMTs, but also significantly influence the modeling accuracy. Therefore, much effort has been devoted to understand and model them.

2.1 AlGaN/GaN HEMT

GaN HEMTs have reached the commercialization phase and are already available from a number of companies, since these devices have shown several outstanding properties such as high power, low noise, high efficiency, etc. These properties enable to make the design of power amplifiers more efficient, compact, easier, and reliable.

In this section, a brief review of vital characteristics, e.g., structure and technology, and basic operation of GaN HEMTs is presented.

2.1.1 AlGaN/GaN HEMT Structure

A detailed description of the GaN HEMT processing technology is beyond the purpose of this thesis but a brief introduction of the GaN HEMT structure would be helpful in understanding the performance of GaN HEMTs.

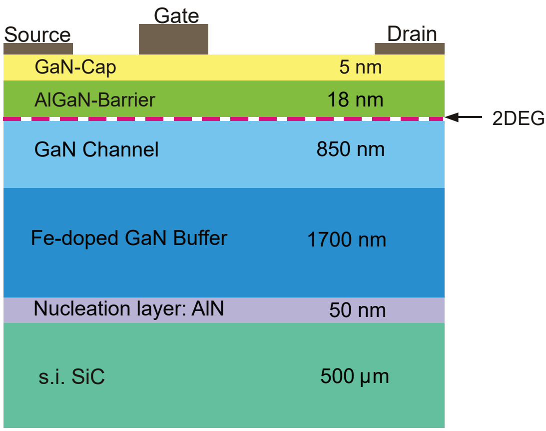


Figure 2.1: The structure of modeled AlGaN/GaN HEMT in this thesis.

The basic concept in a HEMT is the aligning of a wide and narrow bandgap semiconductor adjacent to each other to create a heterojunction. In AlGaN/GaN HEMTs, the carriers from a wide energy gap material (AlGaN) diffuse to the narrow bandgap material (GaN) where a dense two-dimensional electron gas (2DEG as shown in Fig. 2.1) is formed on the GaN side close to the boundary with the AlGaN

[57]. The high sheet charge density of the 2DEG in AlGaN/GaN HEMT combined with the high saturation velocity in the undoped GaN is one of its peculiar useful properties for providing high current densities.

Fig. 2.1 shows the basic structure of modeled AlGaN/GaN HEMT in this thesis. As seen in this figure, SiC is used as substrate [58]. It is one of the best choices for high power applications due to its good thermal performance. In our case, the substrate provides an excellent thermal conductivity of 3.5 W/cm. Besides, sapphire (Al_2O_3) or silicon (Si) are also an option for substrate. They are relatively inexpensive but have worse thermal conductivity.

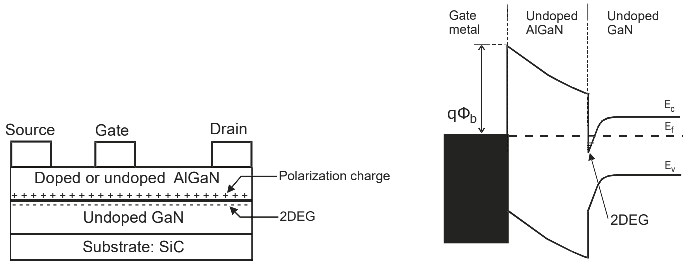
The epitaxial growth of the transistor structure starts with the deposition of a 50 nm thick AlN nucleation layer upon the substrate to reduce the lattice mismatch when growing the GaN layer on the SiC substrate [59]. A 1.7 μm thick Fe-doped GaN layer and a 850 nm undoped GaN layer are then deposited to provide free charge carriers and to increase the electron mobility, respectively. These GaN layers are followed by a 18 nm $Al_{0.25}Ga_{0.75}N$ barrier layer. Finally, the whole structure is capped with a 5 nm thick Si-doped GaN layer (2×10^{18} cm^{-3}) to increase the effective Schottky barrier, which improves the breakdown characteristics and decreases the gate leakage [60].

To summarize, as shown in Fig. 2.1, the AlGaN/GaN HEMT structure used in this thesis consists of 50 nm AlN nucleation layer, 1.7 μm Fe-doped GaN buffer layer, 850 nm GaN layer, 18 nm $Al_{0.25}Ga_{0.75}N$ barrier layer, and 5 nm GaN cap layer on a 500 μm thick semi-insulating SiC substrate.

2.1.2 Basic AlGaN/GaN HEMT Operation

The structure of AlGaN/GaN HEMT takes the advantage of superior transport properties of electrons in a potential well of lightly doped semiconductor material. A simplified AlGaN/GaN HEMT structure is presented in Fig. 2.2.

As shown in this figure, a doped or undoped wide energy gap material (AlGaN) lies on the narrow bandgap material (GaN). This results in a sharp dip in the conduction band edge at the AlGaN/GaN interface as shown in the band diagram of the structure in Fig. 2.2(b). This leads to a high carrier concentration in a narrow region, called a quantum well, along the hetero interface. The distribution of eletrons in the quantum well can be considered as two-dimensional instead of three-dimensional due to its very small thickness. Therefore, the charge density is termed the 2DEG and quantified in terms of sheet carrier density (n_s).



(a) (b)

Figure 2.2: (a) basic configuration of AlGaN/GaN HEMT, (b) band diagram [81].

What is to notice is that, unlike in AlGaAs/GaAs HEMT, a 2DEG is able to be formed at the AlGaN/GaN interface even when the wide energy gap material (AlGaN) is undoped. This is mainly due to the presence of a strong polarization field across the AlGaN/GaN heterojunction. In this way, a 2DEG with the sheet carrier density up to 10^{13} cm^{-2} can be achieved without any doping [1]. As the surface states act as a source of electrons in 2DEG [61], the band diagram and the electron distribution of the AlGaN/GaN heterostructure are changed by the built-in static electric field in the AlGaN layer induced by spontaneous and piezoelectric polarization. Hence, a number of electrons transfer from the surface states to the AlGaN/GaN interface, leading to a 2DEG with high density.

2.2 GaN HEMT Small-Signal Modeling

The first phase in the determination of a HEMT model is the extraction of the extrinsic and intrinsic parameters shown in Fig. 2.3, a standard small signal equivalent circuit for GaN HEMTs, which is inherited from models of GaAs FETs and can also represent the effects found in GaN devices. The linear model extraction is a critical step since this model will lay the initial foundation for the modeling accuracy of final nonlinear model. Direct extraction techniques for determining the small-signal equivalent circuit parameters from S-parameter data have become well known in recent years for FETs and HEMTs [54–56]. In this thesis, the extrinsic parameters will