Chapter 1

Introduction

The High Electron Mobility Transistor (HEMT) or Modulation Doped Field Effect Transistor (MODFET) principle has been published in 1980 by Mimura [1] and Delagebeaudeuf [2] independently as a result of research efforts to improve the microwave behavior of Field Effect Transistors (FET). Since that time researchers all over the world have been working to improve these transistors to achieve higher and higher performance in monolithic microwave integrated circuits (MMIC). Today the HEMT is, besides the Heterojunction Bipolar Transistor (HBT), the state-of-the-art device for microwave ($1 \ldots 30\,\mathrm{GHz}$) and millimeter wave ($> 30\,\mathrm{GHz}$) MMIC applications. To reach such high frequency regimes a device with improved carrier mobility and an adequate noise level is needed. Therefore the formerly used Metal Semiconductor Field Effect Transistor (MESFET) was modified such that heterostructures were introduced to separate mobile charge carriers from fixed ionized impurities to increase their mobility.

HEMTs are meanwhile available in every commercial III-V material system. Although today Silicon-Germanium (SiGe) HBT circuits achieve operation frequencies in the high millimeter wave regime [3] up to 79 GHz [4], for higher frequencies, lower noise level or higher power, compound semiconductors such as Gallium Arsenide (GaAs) and Indium Phosphide (InP) are the dominant materials for HEMT devices in the microwave and millimeter wave regime.

Under current research and development for high power microwave applications, however, Gallium Nitride (GaN) has become the predominant material system among all III-V technologies since it combines the capabilities to operate at high power and high frequency. A comparison with other material systems is shown in Fig. 1.1. GaN-based devices handle very high signal level and bias points due to three terminal breakdown voltages of several hundreds of volts, allowing power densities even twenty times higher compared to GaAs-based devices [27]. Very high power densities then result in power added efficiencies (PAE) close to the theoretical maxi-

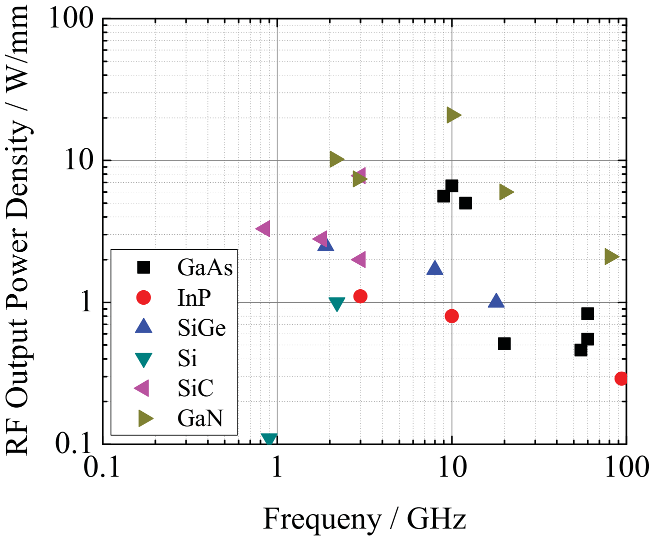

Figure 1.1: Comparison of power vs. frequency capability of Si- and SiC-based [5–13], GaAs- and InP-based [14–22] and GaN-based [23–27] technologies.

mum for each amplifier class. Especially in base station [28] and radar applications high power added efficiency over a very large bandwidth is desired. Since there are applications requiring a bandwidth of more than 100 % of the center frequency [29,30] an intrinsic power added efficiency as high as possible must be provided by the power devices in order to guarantee a high PAE over the whole bandwidth for those wide-band applications.

However, the microwave characteristics of such devices are limited due to non-idealities. Very often the non-ideal behavior is related to trapping effects, but also leakage currents and thermal management play an important role. To reduce or even avoid these non-idealities in order to overcome the limitation in microwave capability of those devices, it is essential to understand the nature and the origin of these effects. To assess non-ideal behavior of devices by electrical and thermal characterization requires various characterization techniques like DC, pulsed IV, small-signal RF, large-signal RF as well as LF and RF noise characterization for the electrical part and micro-Raman thermography as a thermal characterization technique. To investigate the origin of phenomena seen in those kinds of electrical and thermal characterization, physical device simulation is necessary to obtain an insight into the device physics. This kind of investigation of non-idealities in AlGaN/GaN devices for high-power microwave applications is the core intention of this work. It covers all aspects which are of importance to understand the non-ideal behavior of AlGaN/GaN HEMTs in microwave applications. The thesis starts with a brief overview of important material properties of group-III-nitrides in chapter 2. In comparison to other semiconductors it will become clear why GaN is promising for high-power microwave applications. An introduction of the basic operation principle of GaN-based high electron mobility transistor and the physical modelling follows in chapter 3. In chapter 4 then the non-ideal behavior of AlGaN/GaN HEMTs under DC and microwave operation is investigated and discussed in detail. Here, several different characterization techniques are utilized to assess the non-idealities in the devices and device simulations are performed to understand their physical origin. More general aspects for the improvement of the microwave performance of AlGaN/GaN HEMTs will be covered in chapter 5, where the impact of the layout and epitaxial layer sequence on the microwave performance is discussed. In this chapter it will be pointed out that the layout of the devices and the design of the epitaxial layers are as important as the processing in the design and development process of a GaN technology. Finally the thesis will be summarized and conclusions will be drawn in chapter 6.