The Study of Self-Heating Effect of AlGaN/GaN High Electron Mobility Transistors Based on TCAD

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Abstract — As the third-generation semiconductor material, GaN has the characteristics of large forbidden band width and high electron mobility. The AlGaN/GaN high electron mobility transistors (HEMTs) have also attracted attention in recent years. In this paper, the effect of self-heating on device degradation was explored through theoretical analysis and software simulation. Firstly, Silvaco TCAD was used to establish an AlGaN/GaN HEMT single heterojunction model. Then, its self-heating effect was explored by simulation. Besides, it was compared with the theoretical analysis results. The control experiment method was used to compare the I-V output characteristic curve of the device when the self-heating effect was considered, and the relationship between the lattice temperature and the device degradation was researched. According to the research result, when the device is affected by the self-heating effect, the electrical performance of the device degrades obviously due to the increase of lattice temperature.

1. INTRODUCTION

GaN is one of the third-generation semiconductor materials. Because of its large band gap, high thermal conductivity, high breakdown electric field, high radiation resistance, and high electron saturation rate, it has great potential in the manufacturing field of high temperature, high frequency, radiation resistant and high-power devices [1]. Due to the piezoelectric effect and spontaneous polarization effect in AlGaN/GaN heterostructure, two-dimensional electron gas (2DEG) with high electron mobility can be formed at the interface even without doping [2]. However, when AlGaN/GaN high electron mobility transistor (HEMT) works under high bias voltage, the high-power dissipation will rise the device temperature and correspondingly the phonon scattering will also increase, thus reducing the carrier mobility and saturation velocity. The increasing of lattice temperature induced by self-heating effect will directly reduce the electrical performance of transistors and accelerate the degradation [3]. Therefore, in order to deeply understand the physical properties, performance and optimization design of AlGaN/GaN HEMT, the study of its self-heating effect is important. Device design and layer optimization are time-consuming, in this case, a technical computer aided design (TCAD) tool is very useful. It simulates the equipment according to the physical characteristics of the equipment, and analyzes the characteristics of the equipment in the expected environment.

This paper established an analytical model applicable to AlGaN/GaN HEMT DC characteristics with Silvaco TCAD, and analyzed the influence of self-heating effect on AlGaN/GaN HEMT DC I-V characteristics. Furthermore, this paper explored the relationship between the current and the lattice temperature considering the self-heating effect of AlGaN/GaN HEMT. The simulation results show that with the increase of lattice temperature, the drain current of the device will be suppressed.
2. THEORETICAL CONSIDERATION

According to Monte Carlo (MC) study of self-heating effect in GaN/AlGaN HEMTs, the energy transfer from the electron to the lattice causes heat generation in the channel, which is related to the inelastic phonon scattering process of the electron [4]. Hence the self-heating effect will cause the reduction of current.

Furthermore, the increasing of lattice temperature will affect the scattering probability of electrons, which will lead to changes in the rate of local heat generation, leading to different lattice temperature distributions. Therefore, when the grid temperature distribution does not change, the generated heat rate and grid temperature distribution are determined iteratively [4]. Consequently, the iterative method should be applied and the problems should be linearized to solve the electrical characteristics in this simulation.

To judge the influence of self-heating effect, the method of control experiment was adopted. In the simulation, there were two groups of simulated data. The control group was the family of output I-V characteristics under different gate voltages without considering the self-heating effect. In contrast, the experimental group was the family that considers the self-heating effect. In addition, in order to specifically explore the relationship between the current and lattice temperature under the self-heating effect, drain current - lattice temperature at different gate biased and Vds were also simulated.

3. MATERIAL PARAMETERS AND MODELS

The cross-sectional diagram of the investigated AlGaN/GaN HEMT is shown in figure 1, which is a single heterostructure two-dimensional model. The establishment of the model and the reasonable setting of parameters refer to the literature of Tang [5]. The i-GaN buffer layer is 2 μm thick, the i-AlGaN barrier layer is 25nm thick, and the Al component ratio is 30%. The length of source and drain are both 0.5 μm, the length of gate is 1 μm, the spacing between the gate and source is equal to the one between the gate and drain, which is 3μm. The area on the upper surface of the device without electrode coverage was passivated by Si3N4.

![Cross-sectional diagram of the investigated device.](image)

3.1 Contact type
In this simulation, the gate was set as Schottky contact, and the type of contact of the source and drain are both ohmic contact. Generally, the gate contact of Gan-based HEMT devices is Ni/Au structure, and the work function of Schottky contact can be determined by the contact material [5-6]. In this simulation, the work function was set as 4.8eV.

3.2 Models description
In the simulation process, the concentration-dependent and parallel electric-field-dependent mobility models (conmob, fldmob) are adopted considering that carriers are affected by both electric fields and concentrations. The life model (srh) and Boltzmann statistical model were also used in this simulation. In addition, the piezoelectric effect and spontaneous polarization effect were also considered, and calc. strain, a parameter of piezoelectric polarization, was adopted in this simulation. AlGaN dislocation and
the lattice mismatch in GaN material and the substrate structure defects such as the introduction of impurities, the defects in the material form within many body trap [7], because the simulation introduced in many kinds of traps can lead to unpredictable convergence problem, this paper adopted the single trap as approximation of material structure defects, and the largest number of trap is set to 20. For self-heating effect, the lattice heating model (lat. temp) is applied to the simulation of devices. In the process of model solving, Newton iteration method is used, which is the default method of ATLAS calculation for driving-diffusion, and can linearize the nonlinear problems.

4.DEVICE PERFORMANCE AND DISCUSSION
The simulated structure of the AlGaN/GaN HEMT without substrate is shown in figure 2. There is a thin AlGaN layer above the GaN buffer, and 2DEG is polarization-induced in the AlGaN/GaN heterostructure.

![Figure 2 AlGaN/GaN HEMT layer structure without substrate.](image)

In order to determine the gate voltage working range of the simulated device, the relationship between drain current and gate voltage was simulated at first, which can be seen in figure 3. The device can operate properly when gate voltage ranging from -3V to 0V.
Figure 3 The relationship between drain current and gate voltage.

Figure 4 shows a family of output characteristics of the investigated AlGaN/GaN HEMT device without considering the self-heating effect. The curves were simulated at different gate voltages, which are 0V, -1V, -2V and -3V respectively. The cross-marked points mean the curves were formed by calculating the corresponding drain currents at different Vds. What is more, the voltage is calculated at each integer point in the interval from 0 to 30V. According to figure 4, as the gate voltage increases, the currents of the device also increase.
After reaching the saturation region, the curves gradually flatten out. The simulation method for figure 5 is the same as the one for Figure 4. However, it is obvious that the saturation current of the curves considering the self-heating effect is smaller than that of the curves without considering the self-heating effect. In addition, there is an obvious bend for drain currents in the curves in figure 5. It can accelerate electrical migration and thus degrade the gate, and damage the conductor connecting the tube core to the package housing, leading to device failure and a range of reliability issues [8].
In order to further explore the causes of the accelerated degradation caused by the self-heating effect, the effect of lattice temperature on the current was also simulated, as can be seen in figure 6. It can be seen that when the lattice temperature rises due to the self-heating effect, the current shows a downward trend, and the device performance degrades a lot. Besides, the maximum lattice temperature and the power are positively correlated according to the simulation results.
Figure 6 The relationship between drain current and global device temperature considering self-heating effect.

Compared with Monte Carlo's study [4], it is found that the overall trend of I-V curves is the same whether heat generation is considered or not, so the experimental simulation results have high credibility.

5. CONCLUSION
In conclusion, through TCAD simulation, it can be found that the simulation results are basically the same as the theoretical analysis, which is the self-heating effect will cause the reduction of current. In addition, the simulation results are compared with those of Monte Carlo, and the results are consistent with those of Monte Carlo [4]. The self-heating effect of AlGaN/GaN HEMT causes the increase of the lattice temperature, which in turn leads to the drain current to drop, resulting in the degradation of device characteristics. However, the device model in this study is relatively simple, which is an AlGaN/GaN single heterostructure. In addition, this paper does not explore the influence of AlGaN/GaN HEMT self-heating effect on the device on different substrates. Future research will focus on the self-heating effect of AlGaN/GaN HEMT on sapphire and SiC substrates, as these two materials are widely used in the manufacture of AlGaN/GaN HEMT devices due to their advantages in price and performance. Therefore, it is of practical significance to study AlGaN/GaN HEMT on these two substrates.

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