High Temperature Electrical Performances ofn-GaN HEMT

1st Chandra Mohan Lakhinana
Department of electronics and communication engineeringNational Institute of Technology Hamirpur
Hamirpur, Himachal Pradesh-177005
chandulucky250@gmail.com

2nd Vinod Kumar
Department of electronics and communication engineeringNational Institute of Technology Hamirpur
Hamirpur, Himachal Pradesh-177005
vinodsharma@nith.ac.in

***Abstract*—The wide bandgap, high electron mobility, and exceptional thermal stability of GaN HEMTs have led to an increasing recognition of their superior performance in high-temperature applications. This study investigates the electrical performance and material features of GaN HEMTs, with a focus on their dependability at high temperatures. GaN HEMT is simulated from 300K to 900K with Sapphire and AlN as substrates. GaN HEMT used AlN as spacer and n-GaN cap layer is used for surface charge distribution and improving overall device performance. GaN HEMT is checked for electrical properties like on-current, off-current, threshold voltage, subthreshold swing(SS) and transconductance. In thestudy, GaN HEMT with AlN substrate showed better and stable output characteristics compared to GaN HEMT on Sapphire substrate.**

***Index Terms*—GaN HEMT, n-GaN cap layer, on-current, off-current, threshold voltage, subthreshold swing(SS), transconductance**

I. INTRODUCTION

GAN HEMTs are an important breakthrough in semiconductor technology that exhibit superior performance in high-frequency, high-power, and high-temperature applications compared to traditional silicon-based devices [1]. Large bandgaps, high electron mobility, and the ability to function at high temperatures and voltages are among the intrinsic qualities of GaN that make GaN HEMTs particularly appealing for application in power electronics, radar systems, satellite communications, and high-frequency amplifiers. These properties make GaN HEMTs more effective in harsh settings where conventional silicon devices are insufficient.

Even so, there are certain challenges with GaN HEMT performance, particularly at higher temperatures. The activation of the trap state, carrier mobility degradation, and self-heating effects are important challenges. [2] GaN HEMTs show a decrease in drain current and transconductance with increasing operating temperature, mainly because of self-heating effects and increased phonon scattering. Reduced carrier mobility, which is essential to preserving high-speed and high-efficiency operation, is the cause of this performance deterioration. Furthermore, when temperature rises, the threshold voltage of GaN HEMTs falls [2] [3]; this phenomena can be explained by a drop in electron mobility, an activation of trap states, and a reduction in the height of the Schottky barrier. The off-state leakage current increases exponentially as a result of these temperature-dependent effects, making the thermal control of these devices even more challenging.

In high-power and high-frequency applications, efficient thermal management is essential to reduce these temperature-dependent effects and maintaining the dependability and efficiency of GaN HEMTs. [3] To overcome these obstacles and completely utilize the potential of GaN HEMTs at high temperatures, present research endeavors are concentrated on improving device designs, investigating substitute materials, and creating sophisticated thermal control techniques.

Additionally, scaling down of devices was playing an important role in semiconductor industry to making devices more compact. Scaling down of HEMTs allows HEMTs to operate at higher frequencies, and allows for High-power applications compared to HEMTs at higher gate lengths [4]. Scaling down althogh helps in High-power applications of GaN HEMTs also has its own drawbacks. Scaling down leads to high power consumption due to short-channel effects(SCEs), and other parasitic effects [8], which also increase heat distribution density in the device leading to self-heating effects and requirement of GaN HEMT to operate at Higher temperatures.

The use of an n-doped GaN cap layer is a viable strategy to get around these obstacles. The device’s overall electrical performance is enhanced by the n-GaN cap layer’s many functions [6], which include electric field balancing, surface charge distribution, and passivation. By improving the sheet carrier density, stabilizing the threshold voltage, and lowering contact resistance, the n-GaN cap layer helps to lessen some of the negative consequences of device scaling. [6] [7]

It has been demonstrated that adding the GaN cap layer causes HEMTs’ gate leakage current to decrease and their saturation drain current to rise. Additionally, it increases the on/off current ratio of HEMTs, improves subthreshold swing, decreases off-state drain leakage current, and reduces the threshold voltage [9]. GaN HEMT with gate length 90nm is proposed in this paper with an n-GaN cap layer to overcome effects of scaling.

II. STRUCTURE AND DESIGN

GaN HEMT is grown on Sapphire substrate. An AlN nucleation layer which is doped at $10^{17}/cm^3$ is used, to reduce effects due to substrate charges. Spacer layer is grown with AlN material between GaN buffer and AlGaN barrier layers, left undoped for better flow of electrons facilitating current characteristics. Barrier layer is n+doped and a highly doped GaN layer is grown as cap layer to act as passivation layer.

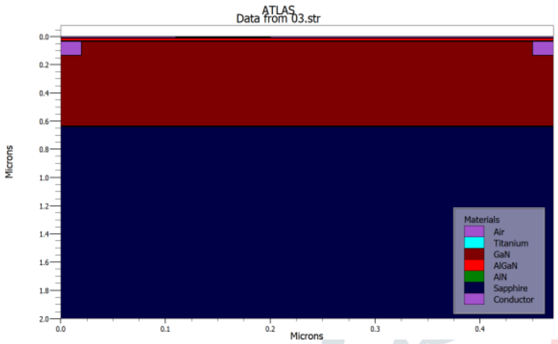

Fig. 1. Structure of HEMT

The dimensions of simulated GaN HEMT with Sapphire as substrate are tabulated below along with doping parameters.

Parameter	Dimension
Gate Length	90 nm
Gate-drain length	90 nm
Gate-source length	135 nm
Gate contact length	5 nm
p-GaN cap layer thickness	2 nm
AlGaN barrier layer thickness	18 nm
AlN spacer thickness	5 nm
GaN buffer thickness	605 nm
AlN nucleation layer thickness	5 nm
Substrate layer (Sapphire)	1360 nm
cap layer doping	p.type, 10^{20}
barrier layer doping	n.type 10^{15}
nucleation layer doping	n.type 10^{17}
Gate workfunction	4.58

TABLE I
MEASUREMENTS OF DESIGNED GAN HEMT

III. SIMULATION RESULTS

The above device is designed on SILVACO TCAD ATLAS simulator, that is used for device physical simulation based on 2D or 3D design.

A. *Transfer Characteristics*

GaN HEMT is simulated at 300K and transient analysis is run at Drain voltage 1V, and Gate voltage variation from -5V to 30V. The output of GaN HEMT with Sapphire and AlN as substrate is tabulated below:

Output Parameter	Sapphire substrate	AlN substrate
Threshold Voltage(mV)	1245	124
On current(mA/um)	8.6987	8.699
Off current(mA/um)	3.20×10^{-23}	1.20×10^{-23}
Transconductance(mS/um)	0.527	0.482
sub-threshold swing(V/dec)	0.8257	0.159
I_{on}/I_{off} ratio	2.72×10^{23}	7.09×10^{23}

TABLE II
TRANSFER CHARACTERISTICS OF GAN-HEMT WITH SAPPHIRE AND ALN SUBSTRATES

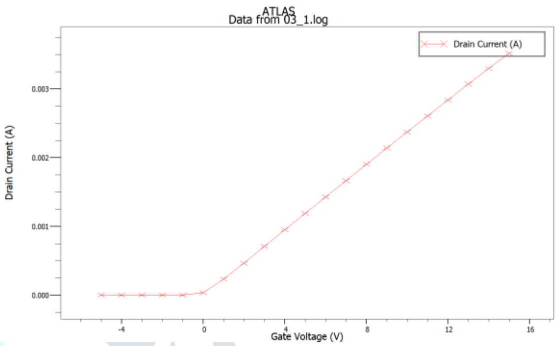

Fig. 2. Transfer characteristics of GaN HEMT with Sapphire substrate

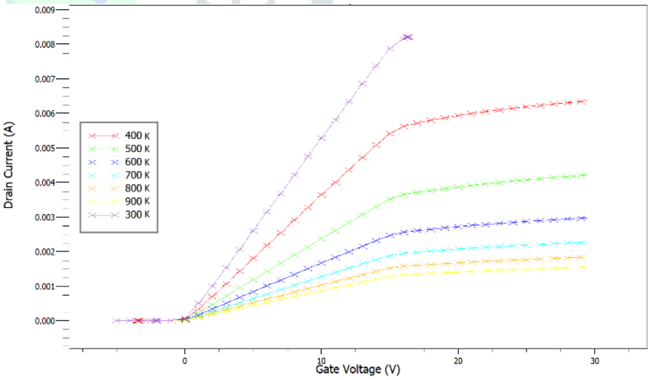

Fig. 3. Transfer characteristics with temperature ranging from 300K to 900K

In figure 2, Transfer characteristics are obtained by operating GaN HEMT with Sapphire substrate with drain bias at 1V, and varying gate bias from -5V to 15V at room temperature. Table 2 represents output characteristics like On-current, Off-current, Transconductance, Ion/Ioff ratio, subthreshold swing(SS) at similat conditions for GaN HEMT with Sapphire and AlN substrates.

Output Parameter	Reference value	Simulated value
Threshold Voltage(mV)	400 [12]	124
On current(mA/um)	1.2 [10]	8.699
Off current(mA/um)	7×10^{-8}[11]	1.20×10^{-23}
Transconductance(mS/um)	0.3 [11]	0.482
sub-threshold swing(V/dec)	0.08	0.159
I_{on}/I_{off} ratio	10^{23}	7.09×10^{23}

TABLE III
COMPARISON OF OUTPUT PARAMETERS OF GAN HEMT ON ALN SUBSTRATE TO REFERENCE PAPERS

B. Temperature Analysis

Drain current and transconductance reduces with increasing temperature due to increased trap states, increased electron collisions, and self-heating effects. Off-current increases exponentially with temperature due to reduced energy states and SHEs.

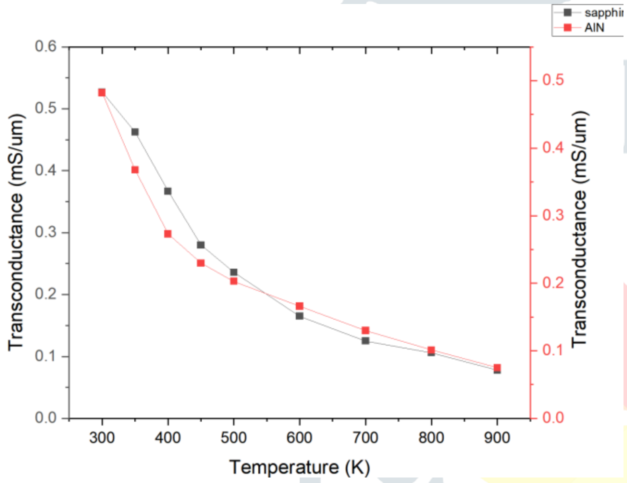

Fig. 4. Behaviour of transconductance with temperature

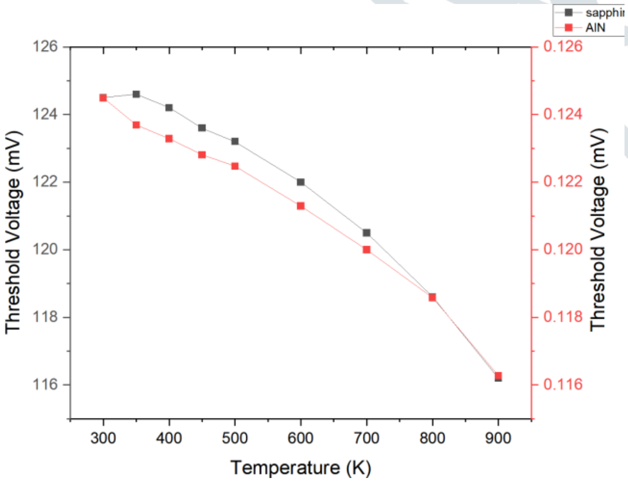

Fig. 5. Effect of Temperature on Threshold voltage

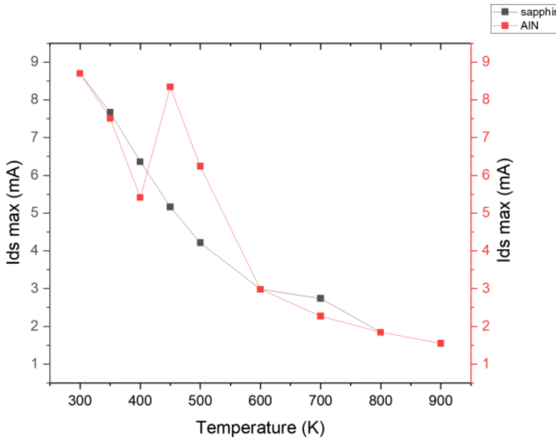

Fig. 6. Behaviour of On-current with temperature

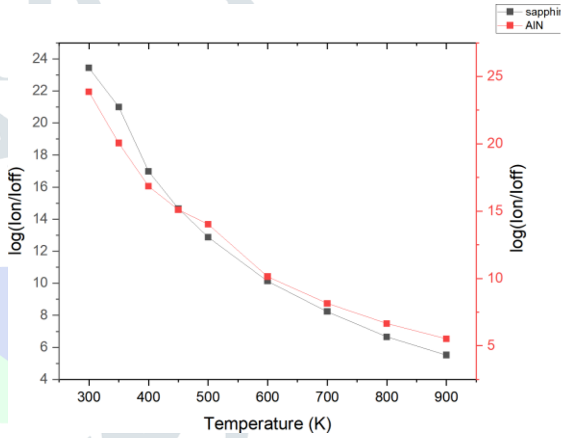

Fig. 7. Alteration in I_{on}/I_{off} ratio with temperature

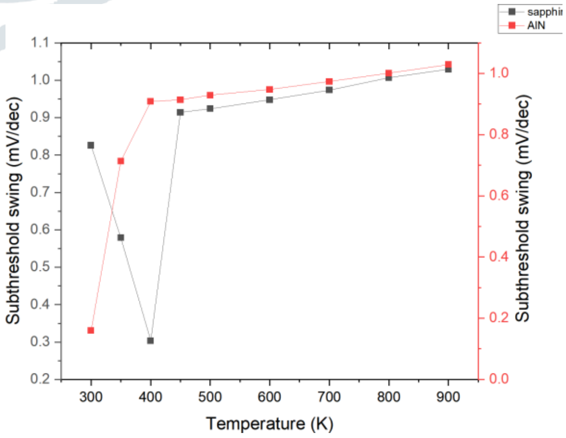

Fig. 8. Influence of temperature on subtheshold swing

IV. DISCUSSION

Aluminium Nitride has better Thermal conductance, Lattice matching and promising electrical properties like dielectric strength compared to Sapphire. Thus, GaN HEMT with AlN as substrate showed better electrical characteristics compared to GaN HEMT on Sapphire substrate. Better thermal conductivity has helped in stable electrical properties at higher temperatures for GaN HEMT on AlN substrate. But Sapphire is more cost-effective than AlN, making it more viable.

GaN HEMT with lesser gate lengths have improved the device switching speed, which can be referred from low but positive Threshold Voltage. In the above device, n-GaN cap layer that is used for passivation had also helped in better electrical properties, by improving electron mobility, reducing gate leakage and better performance at higher temperature by reducing effect of trap states.

V. CONCLUSION

This paper examined electrical performances of 90nm GaN HEMT at high temperatures upto 900K and checked for the influence of substrates like Sapphire and AlN on device performance at higher temperatures. From the simulation results, it was understood that AlN serves as better substrate compared to Sapphire for GaN HEMTs due to its superior material properties.

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