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Self-heating Effects in GaN High Electron Mobility Transistor for Different Passivation Material

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ABSTRACT

In this paper effect of self-heating has been studied of AlGaN/GaN high electron mobility transistor (HEMT) for different passivation layers which is promising device for high power at high frequencies. The different passivation layers used are aluminium oxide (Al_2O_3), silicon nitride (SiN) and silicon dioxide (SiO_2). The device GaN HEMT has been simulated and characterised for its thermal behaviour by the distribution of lattice temperature inside the device using device simulation tool ATLAS from SILVACO. The transfer and output characteristics with and without self-heating has been studied for electrical characterisation. The channel temperature for different passivation observed is 448 K, 456 K and 471 K forAl_2O_3, SiN and SiO_2 respectively. The observed different temperatures are due to difference in their thermal conductivity. This channel temperature information is critical to study the reliability of the device at high power levels.

Keywords: GaN HEMT; Self-heating effect; Passivation material; Numerical simulation

1. INTRODUCTION

Silicon technology has dominated the semiconductor device industry with its established CMOS process since 1960s[1]. But there are some applications like light emitting diodes (LEDs), radio frequency (RF) devices, high temperature and high power electronic devices where III-V nitride compound semiconductor have attracted intense interest[2-4]. These compound semiconductors have excellent performance at high temperature and at high power operations in the microwave frequency range. The AlGaN/GaN HEMT's having wide energy band-gap are emerging as new promising candidates and attracting lot of attention in last decade for next generation RF/microwave sub systems. The AlGaN/GaN HEMT's have much better performances than that of conventional AlGaAs/GaAs HEMT's as these have demonstrated ten times greater output power density[5-8]. Table 1 shows the comparison of some of the important material properties for GaN and other conventional semiconductors materials. Higher current densities which are responsible for higher frequencies and high power performance shift the operating quiescent point of a transistor, results in self heating effects[9-10]. As the current densities increases the channel temperature also rises several hundred degrees above ambient temperature which reduces the reliability and lifetime of the device. Due to self-heating effect thermal resistance increases (R_{th}) which in turn raises the channel temperature. Self-heating is one of the critical factor that reduces device lifetime and reliability as channel temperature can reach much above the ambient base temperature. This effect can burn metal wires connecting the chip to the package, and hence result in device failures and reliability issues.

There are different experimental methods for analysing the device channel temperature such as IR thermal imaging, Raman spectroscopy, thermo-reflectance, infrared microscopy and thermography. The experimental methods are very costly and time consuming, to reduce the cost and time numerical simulation methods are preferred. These are more useful and can be calibrated with any experimental method. The numerical simulation methods are more efficient and alternate approach to study the thermal analysis of high power devices[11-12].

The finite element method (FEM) is used for simultaneously electrical and thermal simulations though it is time consuming and complex.

In the present work ATLAS from SILVACO has been used for simulation of the devices for thermal analysis and electrical behaviour of the GaN based HEMT's using passivation layers of different material.

Table 1. Semiconductor material properties at 300K

Property/Units	GaN	GaAs	Si
Band Gap, Eg(eV)	3.4	1.4	1.1
Electron Mobility (cm^2/Vs)	800	8500	1500
Saturation velocity 10^7 cm/s	2.7	2	1
Breakdown Field (MV/cm)	3.3	0.4	0.3
Thermal conductivity (W/cm-K)	1.3	0.5	1.5
Melting point (ºC)	2773	1510	1690
Dielectric constant	9.0	12.8	11.8

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2. DEVICE STRUCTURE AND PHYSICAL MODELS

The device structure used for simulation ofAlGaN/GaN HEMT's schematic is shown in Fig. 1[13]. It consists of field plate, passivation layer, GaN cap layer, barrier layer and buffer layer grown on silicon carbide substrate. The mole fraction of aluminium in AlGaN barrier layer is 0.2. The gate-drain spacing, gate length and gate-source spacing are 2.7 µm, 0.25 µm and 0.8 µm, respectively. The doping concentration in GaN and AlGaN channels is 1e15 cm^{-3} and 1e16 cm^{-3} respectively. GaN HEMT is grown on silicon carbide substrate because of its higher thermal conductivity. Self-heating effect depends on the thermal resistance and thermal conductivity of material. In this work we considered Al_2O_3, SiN and SiO_2 as passivation materials and there corresponding thermal conductivities are 0.29 W/cmK, 0.185 W/cmK and 0.014 W/cmK, respectively[14-15].

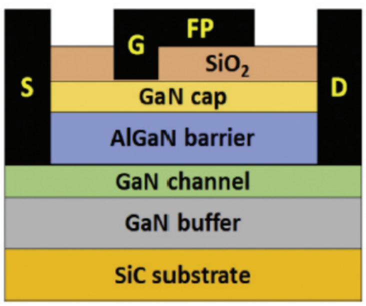

Figure 1. Schematic of AlGaN/GaN HEMT using SiO_2 passivation material.

Various passivation material are studied to improve the performance of HEMT[16-17]. Different models are used in device simulator for simulation of devices and these models consists of many equations such as Maxwell's equations, continuity equation, Poisson's equation and drift-diffusion transport equations[18]. These equations solve the intricacies of the device operation. Different numerical methods are also used to solve these equations for the device structure of different shape and size. The model used in this paper is field dependent mobility model and lattice heating model through GIGA™. High field mobility models are used to examine the alloy scattering effects on electron transport physics. Lattice heat model is used to include the lattice heat flow equation in ATLAS simulation.

$$C = \frac{\partial TL}{\partial t} \nabla(k \nabla TL) + H$$

where

C= heat capacitance per unit volume

κ = the thermal conductivity

H = the heat generation

T_L= the lattice temperature

The above heat equation is solved by Block algorithm which solves this as Newton solution which further solves a decoupled solution of this heat equation. The four equations are solved in a coupled manner by Newton algorithm. Block and Newton are used for low and high temperature respectively. However the combination of both BLOCK and NEWTON methods are used for better efficiency.

3. RESULT AND DISCUSSION

In this section both transfer, output characteristics and channel temperature are analysed for different passivation material. The transfer characteristic are between output drain current and gate voltage of AlGaN/GaN HEMT as shown in Fig. 2 for V_{DS}=6 V. The gate voltage sweeps from -4.0 V to 1.0 V with different passivation material layers. The application of a gate bias greater than the threshold voltage induces a 2DEG concentration in the channel of HEMT. As shown in figure, there is minor effect on drain current of transfer I-V characteristic of different passivation materials i.e. Al_2O_3, SiN and SiO_2.

The output I-V characteristics have been shown in Fig. 3 for different gate bias voltages Vgs=0.0 V, -1.0 V and -2.0 V, for drain voltage V_{DS} is ramped from 0.0 V to 20.0 V. The device is biased at a gate voltage greater than the threshold voltage to

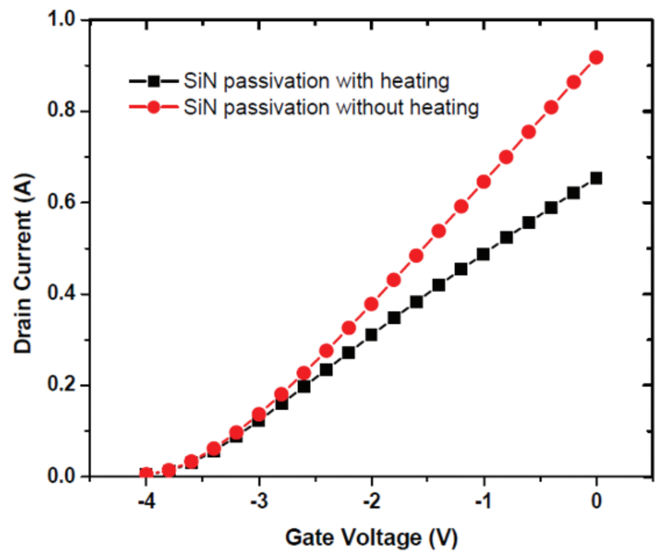

Figure 2. I_{DS}-V_{GS}(transfer characteristics) of AlGaN/GaN HEMT at V_{DS}=20V with and without self-heating.

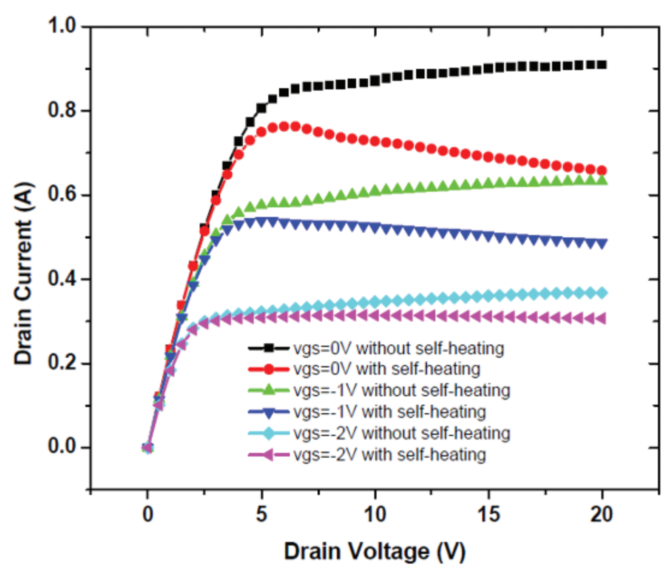

Figure 3. Comparison output I-V curve for AlGaN/HEMT with self-heating and without self-heating.

induce a channel at a constant drain bias. In Fig. 3 SiN material is used for passivation for non-isothermal simulation of output I-V characteristic of device structure. The decrease in drain current at V_{ds} = 20 V with self heating is 28 percent for V_{gs} = 0.0 V. The drain current decreases less for lower gate voltages and 16 percent for V_{gs} = -2.0 V.

Figure 4 show the lattice temperature for gate bias V_{gs} = 0 V and the drain bias V_{ds} = 20 V for AlGaN/GaN HEMT for SiN passivation material layer. The lattice temperature profile shows that the hotspot occurs at gate edge towards drain. Another observation is that these hotspots are closer to the AlGaN/GaN interface which means that most of the hot electrons are restricted to the AlGaN/GaN interface. The mobility degrades rapidly due to high electric fields. The drain current is reduced due to degradation in mobility as shown in Fig. 4. The maximum temperature around the hot spot observed is 456 K at drain voltage V_{ds} = 20 V with SiN passivation material.

The simulations have been carried out for aluminium oxide and silicon dioxide as passivation material, the channel temperature observed is 448K and 471 K for Al_2O_3, and SiO_2 respectively. Figure 5 shows the channel temperature of AlGaN/GaN HEMT by using different passivation material layers with isothermal simulation.

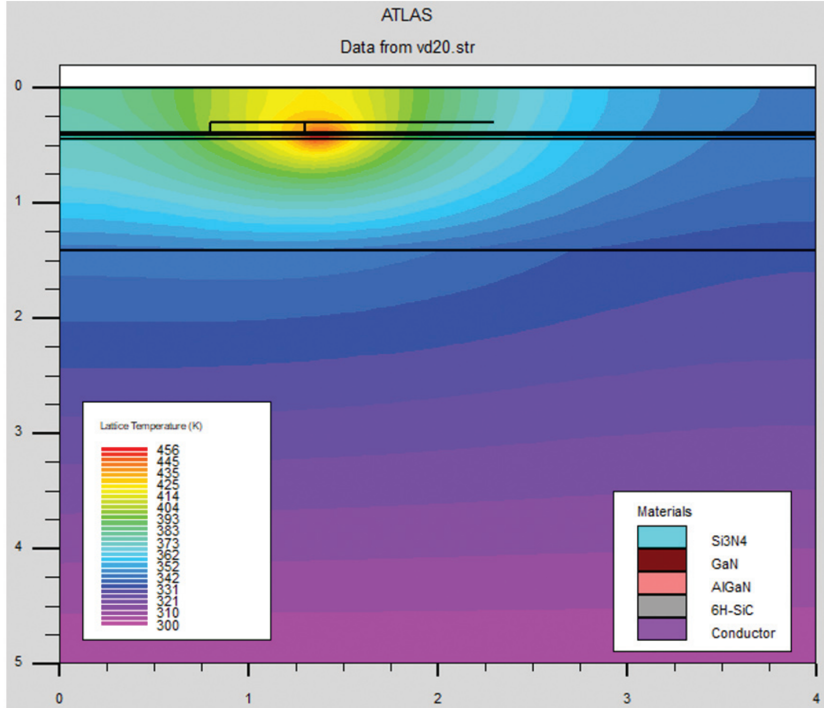

Figure 4. Lattice temperature profile for AlGaN/GaN HEMT with SiN passivation material.

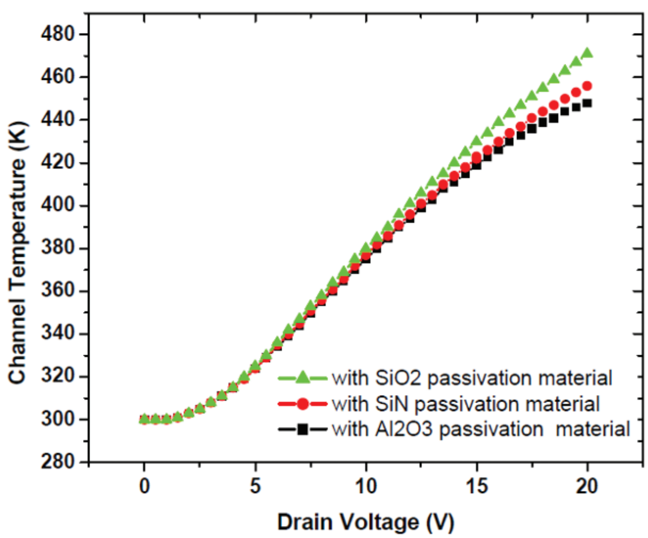

Figure 5. Comparison between the channel temperatures of different passivation materials.

4. CONCLUSION

The rigorous simulations have been carried out for three passivation materials i.e. aluminium oxide, silicon nitride and silicon dioxide of same thickness approximately 400 nm. The transfer characteristics have little effect of isothermal simulation while output characteristics have significant reduction in output current due to self-heating. The channel temperature of AlGaN/GaN HEMT has been observed for different passivation materials and it observed as 448 K, 456 K and 471 K for Al_2O_3, SiN and SiO_2 respectively. The lowest temperature is for aluminium oxide. This study will be useful to evaluate the device reliability and its performance.

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