Thermal and Electrical Performance of AlGaAs/GaAs based HEMT device on SiC substrate

Preethi Elizabeth Iype¹, V Suresh Babu², Geenu Paul¹

¹St. Thomas Institute for Science & Technology, Trivandrum, Kerala, India;
²Government Engineering College, Wayanad, Kerala, India.

Abstract. In this paper investigation on electrical and thermal performance of the AlGaAs/GaAs HEMT device is carried out by comparing the device grown on substrates like 4H-SiC and Sapphire. The investigation was carried out based on Silvaco TCAD Atlas simulation. The DC characteristics of the device with varying ambient temperature were evaluated. A deterioration of drain current from 0.9 mA to 0.5 mA is observed as temperature rises from 300K to 500K on 4H-SiC substrate. The HEMT grown on 4H-SiC substrate has a high power dissipation, resulting in reduced temperature compared to sapphire substrate. This increases the lifetime of the device by 1000s of hours and also its overall performance. The HEMT proposed here is found to have an electrically and thermally optimal performance on 4H-SiC substrate than on sapphire

Keywords: HEMT; TCAD; ambient temperature; thermal conductivity

1. Introduction

There is a huge demand for high speed communication, which has resulted in a number of novel microwave nano scaled devices. High Electron Mobility Transistors (HEMT) are the new generation transistors which have revolutionized the communication sector like mobile, satellite, radar etc. The HEMT has a number of properties to its credit like superior transport, high mobility and velocity of electrons[1-3]. The dimensions of the structure particularly the gate length and the material parameters needs to be considered, while modeling for obtaining optimum performance. The bandgap formed between the two heterostructures has a discontinuity in the conduction band and valance band. This creates a quantum well in the conduction band. The wideband gap semiconductor is heavily doped, while the lower bandgap semiconductor is undoped. This causes a movement of electrons from the heavily doped to the undoped forming a quantum well called the 2DEG at the interface. It confines the movement of electrons in this well. Lattice matched HEMT structures with same lattice constant and different bandgaps need to be used [4]. Lateral type HEMTs is quite mature and is promising candidate for high power applications. Mobility of GaAs devices are comparatively higher compared to the GaN devices which can improve the drain current [5]. This results in lower parasitic drain and source resistances. The increase in lattice temperature arises due to self-heating effects occurring at high operating voltages thus reducing the current due to low mobility [6]. This affects the performance of HEMT devices. The thermal performance of the device is much superior with 4H-SiC as substrate compared to the device with sapphire as substrate. GaAs has a bandgap of 1.42 eV compared to 1.1eV of Silicon. The large bandgap of GaAs makes the device smaller in size with greater thermal stability, higher thermal conductivity and higher breakdown voltage [7]. Due to its direct bandgap it can be used...
as a radiation resistant material. This work provides a novel approach for the evaluation of thermal characteristics of a GaAs based HEMT device with 4H-SiC substrate for different temperatures 300K, 400K and 500K, in order to obtain a thermally and electrically efficient system.

2. Proposed Device Structure and Material Properties

AlGaAs/GaAs HEMT structure uses a wideband gap semiconductor AlGaAs which is aligned next to low band gap semiconductor GaAs to form a heterojunction. The carriers from the heavily doped AlGaAs are transported to the narrow bandgap material GaAs via diffusion. A 2DEG quantum well is formed in the channel near the AlGaAs interface. This is the predominant feature which makes HEMT useful in high power and high frequency devices. The structure of the well formed is dependent on the substrate material, dopant concentration and growing method.

Increase in lattice temperature changes the material properties like bandgap and mobility. Numerical simulations are performed using drift diffusion model and performance parameters like joule heating, lattice temperature, thermal conductivity and potential are analysed for the HEMT structure. The drain and transfer characteristics are observed for increase in temperature. The structure proposed in figure 1 uses thickness of channel of GaAs as 25nm, doped AlGaAs as 30nm, and channel length as 100nm.

The 2DEG density reaches a peak of $8 \times 10^{14}$ cm$^{-2}$ for GaAs based devices compared to GaN, which reaches $1.2 \times 10^{14}$ cm$^{-2}$ at gate voltage of 4.5V. Schrodinger’s wave equation and Poisson’s equation are solved self consistently by the Silvaco TCAD to realize the 2DEG. GaAs is not much sensitive to overheating due to wider energy band gap. Bandgap decrease with increase in temperature resulting in a rise in amplitude of atomic vibrations, consequently increasing the interatomic spacing [8-10].

Performance deteriorates with self- heating issues which occurs at high output voltages. The increase in lattice temperature results in decrease in mobility, which in turn reduces output current indirectly degrading the performance of the device. Silicon substrates help in controlling the self-heating problems in HEMT to a large extent [11-14]. Here two other materials like 4H SiC and Sapphire are used as substrate to find an alternative for Si [15-16]. A thermal model needs to be simulated to understand the heat flow from the active to substrate regions as well as the hot spot regions in the GaAs based HEMT. Thermal resistance is calculated using equation (1)
In the proposed work, the performance of HEMT devices for different thermal parameters like heat conductivity, lattice temperature, joule heating, potential are being analysed using the Silvaco TCAD.

\[
R_{TH} = \frac{1}{\pi k_S} \ln \left( \frac{8 t_S}{\pi L_G} t_{Si} \right)
\]

(1)

where \(t_{Si}\) is substrate thickness, \(L_G\) is gate length and \(k\) is thermal conductivity.

The thermal resistance and channel temperature along with power dissipated can be related using

\[
P_{\text{diss}} = \frac{T_{\text{sub}} - T_{\text{sub1}}}{R_{TH}}
\]

(2)

where \(T_{\text{sub1}}\) is substrate temperature [17-19].

Dissipated power is the sum of all terminal currents multiplied by the voltages.

\[
P_{\text{diss}} = \sum IV
\]

(3)

The heat equations used for the analysis of thermal performance in the device applied under drift diffusion model is

\[
\frac{CBTL}{\partial t} = \nabla (k \nabla T) + H
\]

(4)

where \(C\) is the heat capacitance per unit volume, \(T\) is the local lattice temperature, \(k\) is thermal conductivity and \(H\) is heat generation

Expressed as

\[
H = \left( \frac{|n|}{q} \mu n + \frac{|p|}{q} \mu p \right) + q(R - G)[\varepsilon p - \varepsilon n + TL(P_p - P_n)]
\]

(5)

where,

\[
\frac{|n|}{q} \mu n + \frac{|p|}{q} \mu p
\]

is the joule heating term

\[
q(R - G)[\varepsilon p - \varepsilon n + TL(P_p - P_n)]
\]

is generation and recombination heating and cooling term for a device to perform optimally it is vital to understand the temperature dependence of thermal conductivities of various substrate materials used.

The thermal conductivities for SiC and Sapphire at different temperatures can be calculated from the equations (6) and (7) respectively.

\[
K_{\text{SiC}}(T) = 3.4(T/300)^{-1.5} \text{W/cm-K}
\]

(6)

\[
K_{\text{Sapphire}}(T) = 0.49(T/300)^{1} \text{W/cm-K}
\]

(7)

The device is separated from the substrate by a low thermal conductivity buried SiO\(_2\) layer. There is large surface scattering of phonons due to low thermal conductivity in thin film surface [20-21].

3. Methodology

There is a high demand for advanced design system for the development of nano semiconductor devices. The electrical and thermal performance of a device can be evaluated by the TCAD Silvaco for the
simulation of the microelectronic device. The internal physical mechanisms for the device operation can be simulated for the specific semiconductor structures modelled. The drift diffusion model in Silvaco TCAD is used for the numerical simulation and analysis of self-heating in the device. The lattice heat model an extension of the drift diffusion is used to analyse the heat dissipation in the HEMT device. The charge carriers in the lattice are in thermal equilibrium. Poisson, electron hole continuity equations, lattice heat flow equations are solved in the simulation. The transfer characteristic obtained in figure 2, for $V_{GS}$ of 0V shows the drain current gradually increasing after gate voltage crosses 0V. The drain current increases and attains saturation of 0.7mA after the gate voltage of 0.6V.

![Figure 2. Comparative Transfer Characteristic for Sapphire and SiC substrates](image)

The output drain characteristic of the device is plotted as in figure 3. There is a sharp rise in drain current at 0V and at 0.3V there occurs steady increase. It indicates a variation in the density for 2DEG which depends on the gate source voltage applied[14-16]. There occurs a variation in the concentration of electrons and correspondingly the electron density due to change in gate source voltage. Thermal conductivity of SiC is 4.9W/cm-k and that of sapphire is 1.7 W/cm-k. The thermal conductivity decreases with increase in temperature for Sapphire and SiC [17-22].

4. Results

To evaluate the electrical performance of the HEMT with change in ambient/lattice temperature drain characteristics are generated for 300K, 400K and 500K as in figure 4. It is observed that with increase in temperature the drain current steadily deteriorates towards the saturation region by 1mA for every 1V change in drain voltage.
Similarly, in the transfer characteristic, in figure 5, increase in temperature leads to decrease in drain current as it reaches the saturation region. Drain current decreases from 900 mA/mm at 300K to 600mA/mm at 500K. Temperature dependent effects remarkably influence the behaviour of output current ($I_D$), threshold voltage ($V_{th}$) and transconductance ($g_m$). Self-heating effects (SHE) occurs due to the generation of heat in transistor channel, caused by the transfer of energy from hot electrons to lattice[22]. This reduces the average electron velocity due to increased phonon scattering mechanisms. At high temperatures SHE becomes very predominant. Also the increase in gate width increases the power level and subsequently increases heat dissipation. The carrier velocity decreases with increased scattering due to thermal vibrations of the lattice. This lowers the low field mobility and saturation velocity.

**Figure 4.** Output Characteristics (SiC substrate) for different temperatures

**Figure 5.** Transfer Characteristics (SiC substrate) for different temperatures.
The bell shaped transconductance curve of the AlGaAs/GaAs HEMT device shown in figure 6 reaches a peak of 1.4 mS/µm and declines to 0.8 mS/µm at 300K. With increase in ambient temperatures of 400K and 500K the gm reduces to 1 and 0.8 respectively. Self-heating within the device becomes predominant at high voltage bias conditions which results in subsequent decrease in the transconductance. The gm is observed to be slightly linear with increase in gate bias.

4.1 Heat Conductivity

The substrate material used in the device plays a vital role in determining the heat conductivity and dissipation of heat for the optimal thermal performance of the device. The gate length considered is also of prime importance. The 4H-SiC material used as substrate has got high thermal conductivity of 3.7 W/cm°C. Increase in lattice temperature causes self-heating within the device. The two heat conductivity profiles are as obtained in figure 7a and figure 7b on Sapphire and 4H-SiC substrates. Heat conductivity reaches a maximum of 0.433 for sapphire and 2.6 for 4H-SiC thus making the 4H-SiC thermally more efficient in the proposed HEMT structure. The high heat conductivity on 4H-SiC substrate allows more heat to be dissipated from the device than on sapphire substrate.

The lower the thermal resistance of the substrate material the greater the amount of heat flow in the device. This results in a maximum drain current flow of 1000 mA/mm at Vgs=0V for gate length of 100nm.
4.2. Lattice Temperature:
Lattice temperature profile is an important parameter to understand the reliability of GaAs HEMT. The 4H-SiC used as substrate is a wideband material compatible with GaAs. It has high thermal conductivity and low thermal expansion which makes it thermally more stable. From the lattice temperature profile obtained in figure 8, it is observed that the temperature is minimum at about 308K below the surface gradually increases and attains a maximum value of upto 316K towards the substrate or body. The 4H-SiC substrate for the device has higher temperature towards the drain gate interface due to the electron temperature being highest there. The temperature extends towards the gate channel interface. This results in decrease of mobility due to high electric field and subsequently low drain current. The temperature rises upto 316K towards the drain end.

4.3 Joule Heating
Joule Heating is the amount of heat generated by the energy of current flowing through the conducting device. The thermal energy rises with respect to the thermal conductivity of the substrate material. Cutline through the centre of device indicates a slight increase in temperature towards the drain region. Joule heating profile in figure 9 shows an increase upto 1.32 eV towards the drain gate interface due to increase in current towards that end.
4.4 Potential
The potential is seen to increase up to 1.46 V due to increase in temperature and create hot spot region towards the drain gate end in Figure 10. This arises due to voltage difference occurring due to the bias voltage of Vds of 3 V applied.

5. Conclusion
The AlGaAs/GaAs HEMT on 4H-SiC substrate is suggested as a better device than over sapphire substrate. Thermal evaluation has been done in this work to analyse the electrical performance of the device with change in ambient temperature. Parameters like lattice temperature, joule heating, heat conductivity and potential have been evaluated by simulating the device using Silvaco TCAD. Regions towards the drain gate interface is observed to undergo self-heating due to the large current flow towards the drain region. The lattice model is used in drift diffusion model in order to evaluate the heating profile. Output and Transfer characteristics of the device is observed for different temperatures. The electrostatics at the gate drain edge is crucial for determining the optimal performance of the device. Because of the lattice match between 4H-SiC and AlGaAs and due to its better thermal conductivity the HEMT device proposed in this work can be considered as an optimal device for electrical and thermal performance applications.
References

[1]. Xuesong Chen, Slim Boumaiza, and Lan Wei 2019 Self-Heating and Equivalent Channel Temperature in Short Gate Length GaN HEMTs, *IEEE TRANSACTIONS ON ELECTRON DEVICES*, VOL. 66, NO. 9

[2]. Ahsan, S. A. 2017. Modeling and analysis of GaN HEMTs for power-electronics and RF applications modeling and analysis of GaN HEMTs for power-electronics and RF applications Indian Institute of Technology Kanpur

[3]. Arivazhagan, D. Nirmal, J. Ajayan, D. Godfrey, J. S. Rakkumar, and S. Bhagya Lakshmi 2019 Modeling of self-heating for AlGaIn/GaN HEMT with thermal conductivity degradation effect *AIP Conference Proceedings* 2201, 020010 https://doi.org/10.1063/1.5141434

[4]. Adarsh Nigam, Thirumaleshwara N. Bhat, Saravanan Rajamani, Surani Bin Dolmanan, Sudhiranjan Tripathy, and Mahesh Kumar B., Zhou, Q., Qin, J., & Wang, H. 2017. Effect of self-heating on electrical characteristics of AlGaN/ GaN HEMT on Si (111) substrate, Cite as: *AIP Advances* 7, 085015 https://doi.org/10.1063/1.4990868

[5]. Nandha Kumar Subramani Physics-based TCAD device simulations and measurements of GaN HEMT technology for RF power amplifier applications 2018 *HAL Id* https://tel.archives-ouvertes.fr/tel-01702325

[6]. Moumita Bhoomik 2013 Electrical Characteristics of GaAs Nano-HEMT International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-3, Issue-2

[7]. S. Arulkumaran a, Z.H. Liu b , G.I. Ng, W.C. Cheong, R. Zeng, J. Bu, H. Wang, K. Radhakrishnan, C.L. Tan, 2007 Temperature dependent microwave performance of AlGaIn/GaN high-electron-mobility transistors on high-resistivity silicon substrate , *Thin Solid Films* 515(10):4517-4521

[8]. Saleh Kargarrazi, Ananth Saran Yalamarthi, Peter F. Satterthwaite, Scott William Blankenberg, Caitlin Chapin, and Debbie G. Senesky, 2019 Stable Operation of AlGaN/GaN HEMTs for 25 hours at 400°C in air, , *IEEE Journal of the Electron Devices Society* PP(99):1-1

[9]. Sayed Ali Albahrani, Dhaval Mahajan, Saleh Kargarrazi, Dirk Schwantuschke, Thomas Gneiting,, Debbie G. Senesky and Sourabh Khandelwal , 2020 "Extreme Temperature Modeling of AlGaIn/GaN HEMTs," in *IEEE Transactions on Electron Devices*, vol. 67, no. 2, pp. 430-437, doi: 09/TED.2019.2960573

[10]. Sana Firoz, R.K. Chauhan, 2011, COMPARISION OF AlGaN/GaN AND AlGaAs/GaAs BASED HEMT Device under doping consideration, *Materials Science*

[11]. Man Hoi Wong, Yoji Morikawa, Kohei Sasaki, Akito Kuramata, Shigenobu Yamakoshi, and Masataka Higashiwaki(2016) Characterization of channel temperature in Ga2O3 metal-oxide-semiconductor field effect transistors by electrical measurements and thermal modeling Citation: *Appl. Phys. Lett. 109*, 193503 (2016); doi: 10.1063/1.4966999

[12]. Abderrazzak El Boukili, 2013 Physical Modeling and Simulation of Thermal Heating in Vertical Integrated Circuits, *International Journal of Computer Science & Engineering Survey* 4(2), DOI:10.5121/ijces.2013.4201

[13]. Mohammad Abdul Alim, 2012 Thermal and Small-Signal Characterisation of GaAs and GaN Pseudomorphic High Electron Mobility Transistors (pHEMTs) A thesis submitted to The University of Manchester for the degree of MPhil In the Faculty of Engineering and Physical Sciences

[14]. Manju K. Chattopadhyaya., Sanjiv Tokekarb a School of Electronics, Devi Ahilya University, Indore 2008 Thermal model for dc characteristics of algan/gan hems including self-heating effect and non-linear polarization, *Microelectronics Journal*, Volume 39, Issue 10, Pages 1181-1188

[15]. Yuhao Zhang, Min Sun, Zhihong Liu, Daniel Piedra, Hyung-Seok Lee, Feng Gao, Tatsuya Fujishima, and Tomás Palacios, (2013) Simulation and Thermal Performance Study of GaN Vertical and Lateral Power Transistors
[16]. Muhammad Navid Anjum Aadit, Sharadindu Gopal Kirtania, Farhana Afrin, Md. Kawsar Alam and Quazi Deen Mohd Khosru High Electron Mobility Transistors: Performance Analysis, Research Trend and Applications http://dx.doi.org/10.5772/67796

[17]. Dragica Vasileska, Chair Stephen Goodnick Michael Goryll, 2013 Study of Self-Heating Effects in GaN HEMTs by Towhid Chowdhury, A Thesis submitted to Arizona State University

[18]. E. R. Heller and A. Crespo, Jan. 2008, “Electro-thermal modeling of multifinger AlGaN/GaN HMET device operation including thermal substrate effects,” Microelectron. Rel., vol. 48, no. 1, pp. 45–50.

[19]. X. Deng, B. Zhang, and Z. Li, December 2007, “Electro-thermal analytical model and simulation of the self-heating effects in multi-finger 4H-SiC power MESFETs,” Semicond. Sci. Technol., vol. 22, no. 12, pp. 1339–1343.

[20]. N. Killat, M. Montes, J. W. Pomeroy, T. Paskova, K. R. Evans, J. Leach, X. Li, U. Ozgur, H. Morkoc, K. D. Chabak, A. Crespo, J. K. Gillespie, R. Fitch, M. Kossler, D. E. Walker, M. Trejo, G. D. Via, J. D. Blevins, and M. Kuball, 2012 “Thermal properties of AlGaN/GaN HEMTs on bulk GaN substrates,” IEEE Electron Device Lett., vol. 33, no. 3, pp. 366–368.

[21]. A. Bar-Cohen, J. D. Albrecht, and J. J. Maurer, October 2011, “Near-Junction Thermal Management for Wide Bandgap Devices,” in IEEE Symposium on Compound Semiconductor Integrated Circuit, Waikoloa, HI, pp. 1–5.

[22]. A. Caddemi, G. Crupi, N. Donato, 2005, “Temperature effects on DC and small signal RF performance of AlGaAs/GaAs HEMTs”, Elsevier