Electro-thermal Comparative Analysis and Simulation of Wide Band Gap Semiconductor Materials for Power Electronic Devices

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Abstract: *Power electronics switching devices involving Wide Band Gap (WBG) materials such as silicon carbide (SiC) and gallium nitride (GaN) provide a substantial switching level improvements as compared to the silicon (Si) devices. Recently Si MOSFETs are also being superseded by silicon carbide (SiC) and gallium nitride (GaN) MOSFETs due to their superior performance in high temperature limits. In order to directly compare these two types of MOSFETs we study their various parameters like energy band gap, carrier mobility, saturation velocity and thermal conductivity. A study has also been conducted to see the effect of high temperatures on electrical properties. A circuit analysis tool Pspice is used to study these two types of MOSFETs.*

Key words: *SiC, GaN, MOSFET, Wide Band Gap Power Devices*

1. Introduction

In high temperature electronic applications, thermal reliability of power switching devices play a key role. In high frequency domain (e.g. High Voltage DC transmission), the rapid increase in application of power converters demands a highly reliable device for efficient power conversion [1]. And a top end instrument should perform efficiently and produce good results at high temperature levels. In the recent years, very important semiconductor materials: SiC and GaN have been discovered, having the capability to work at the required speed, temperature and voltage conditions [2]. Moreover, such high operating conditions are not bearable by the exiting silicon (Si) based technology. In today's system application devices, the need for high temperature switches results in a great progress in WBG. In order to enhance the performance of MOSFET, the key parameters include band gap optimization, sub threshold leakage issues, carrier mobility and saturation velocity. In future power converters (WBG) semiconductors will be preferred over Si based [3].This is because of their superior material properties, as shown in Figure 1. By using these advanced power semiconductor materials, the effectiveness of the electrical energy conversion will be enhanced for a more balanced use of electrical energy.

Full-bridge bidirectional converters are very famous in high and medium power application because of several benefits such as: high conversion ratio, inherent galvanic insulation between input and output and reduction in passive component sizes due to increase in inductor current frequency to twice the switching frequency. Employment of WBG devices in power converters results in reduction of device losses and thermal management system [5].

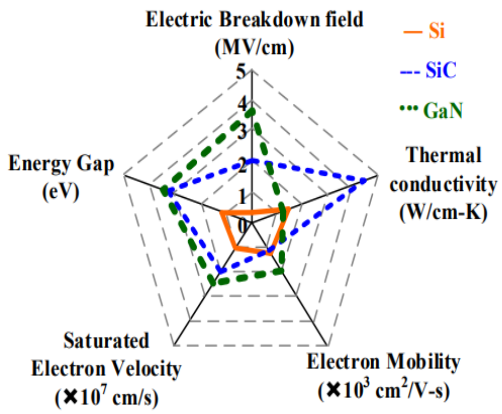


Figure 1. Comparison of material properties of Si, SiC and GaN [4]

SiC offers high thermal performance, single-chip SiC MOSFET can operate at 1700V and 50 amps of current [6]. On the other hand GaN is suitable for high switching application as having high carrier mobility with break down voltage up to 650 V. Applications such as Electric Vehicles (EV's) and aerospace with limited battery storage demands DC-DC power converters having small size, high power density and reliability which makes WBG devices very strong candidates for such applications. GaN and SiC power devices work at higher voltages, frequency and temperature, helping to reduce up

to 90% of the power losses in power conversion. GaN is used in many applications in high power electronics, light-emitting diodes and ultra-power switches because of its wide band gap of 3.4 eV at room temperature [7]. GaN is also utilized in high-electron-mobility transistors, quantum wells, photo detectors, and display devices. The objective of this study is to examine the thermal and electrical properties of SiC and GaN MOSFET at different temperature range and provide a comparative analysis among these properties. The electrical characteristic curves for both SiC and GaN based MOSFET are analyzed at room and high temperatures using Pspice.
The remaining paper is organize as; in section II covers discussion on simulations of temperature dependent characteristics of GaN and SiC, section III discusses the simulation results of electrical characteristics of SiC and GaN transistor at different temperatures, section IV is conclusion.

Symbols

E_g	Energy band gap
T	Temperature
eV	Electron volt
μ_V	Carrier mobility
V_{sat}	Saturation velocity
A_n	Temperature coefficient
T_L	Lattice temperature
$\lambda (T_L)$	Thermal conductivity
λ	Channel-length modulation parameter
μ_n	Charge-carrier effective mobility
L	Gate length
C_{OX}	Capacitance of oxide layer
W	Gate Width
A	Material specific constant
B	Material specific constant
γ	Un-doped mobility changes due to lattice scattering
V_{GS}	Gate to source voltage
V_{DS}	Drain to source voltage
I_D	Drain current
V_{th}	Threshold voltage
K, B, m, n	Linear and saturation region characteristics control parameters

Abbreviations

MOSFET	Metal-Oxide Semiconductor Field-Effect transistor
HEMT	High Electron Mobility Transistor

2. Simulation of Temperature Dependent Characteristics

In this section temperature dependency of materials properties is discussed and comparison is performed among energy band gap, carrier mobility, saturation velocity and thermal conductivity.

A. *Energy Band-Gap*

The semiconductor conductivity is hugely based on the band-gap. The energy band-gap is directly affected by the temperature according to Varshni's equation [8].

$$E_g(T) = \mathrm{E}_g(0) - \frac{\alpha_E T^2}{T + \beta_E} \qquad (1)$$

Where, $E_g(0)$ is energy band-gap at absolute zero kelvin and α_E and β_E are material specific constants. The values of constants for the specified materials are shown in the Table I.

TABLE I. ENERGY BAND GAP PARAMETERS

Material	$E_g(0)eV$	$\alpha_E(eV/K)$	$\beta_E(K)$
SiC	3.26	3.3e-2	1.0e5
GaN	3.40	9.09e-4	800

The band gap values of SiC and GaN are of 3.26 eV and 3.4 eV respectively which is higher than Si band gap which is 1.1 eV. The relation between temperature and energy band-gap of SiC and GaN is presented in Figure 2. At room temperature, GaN has a greater value than SiC. The decay in the curve of GaN is sharper than SiC. For this reason, SiC has a higher value of band gap at high values of temperature. But still it is evident that SiC and GaN have greater value than Si, even at very high temperatures.

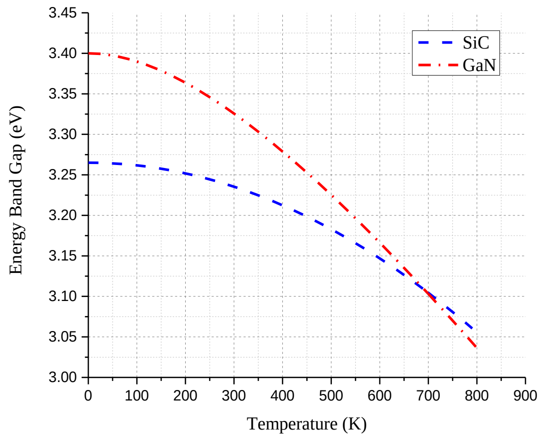


Figure 2. SiC versus GaN Energy Band Gap temperature dependency

B. *Carrier Mobility*

Carrier mobility is examined to be one of the most fundamental dependent MOSFET constrain. The carriers are generally electrons and holes. Conductivity of a semiconductor (material) is directly dependent on the combination of carrier concentration and mobility. Temperature, charge carrier and impurity concentration are the factors that affect the carrier mobility. In this paper, we only discuss the relation of carrier mobility and temperature for SiC and GaN. From Bose-Einstein distribution, the phonon scattering strongly depends on temperature. As with the rise in temperature, phonon density increases which results in increase of scattering [9]. This lattice scattering results in lowering the carrier mobility at higher temperatures. Equation 2 shows the relation of temperature
and carrier mobility [10]. Material properties are shown in Table II.

$$\mu_v = \mu_{v300K} \cdot \left(\frac{T_L}{300K} \right)^{\gamma} \tag{2}$$

Where, T_L is variable temperature, γ is a constant that specifies how the un-doped mobility changes due to lattice scattering and $\mu_{V300\ K}$ is carrier mobility at room temperature (cm^2/Vs).

Table II Carrier mobility parameters

Material	μ_{V300K} (cm^2/Vs)	γ
SiC	950	-240
GaN	1600	-1.5

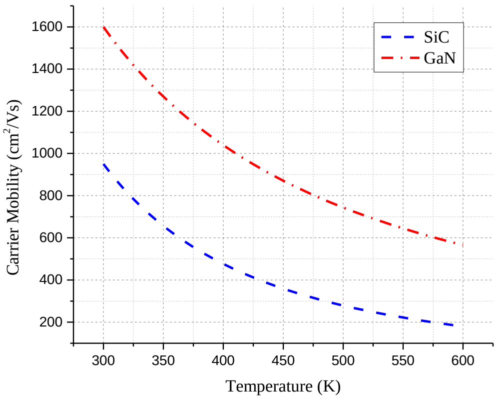


Figure 3. Carrier mobility versus temperature

Larger electron mobility and saturation velocity allow for higher frequency operation. SiC has larger electron mobility as compared to Si, whereas GaN's electron mobility is even larger than SiC, which shows that GaN is the best semiconductor device for very high frequencies. The carrier velocity of SiC and GaN at room temperature is 950 and 1600 cm^2/Vs as shown in Figure 3.

C. *Saturation Velocity*

High-end devices, which are the high electron mobility transistor (HEMTs), gain is directly proportional to the saturation velocity [11]. Under the application of high electric field, carrier velocity attains its maximum value and saturates. Further increase in field results in energy loss through lattice interactions. These interactions causes phonon and photon emission, which enhances the temperature of the device. And this increase in temperature can ultimately affects the whole results of the device. The relation between saturation velocity and temperature is represented by Equation 3.

$$V_{sat}(T_L) = \frac{v_{sat300}}{(1-A_n) + A_n \cdot \left(\frac{T_L}{300K} \right)} \tag{3}$$

Where, V_{sat} (300k) is saturation velocity at room temperature, A_n is temperature coefficient of material and T_L is variable temperature. WBG materials (SiC and GaN) have lower relative permittivity and larger saturation velocity than Si. SiC saturation velocity is 2×10^7 cm/s and GaN is 2.2×10^7 cm/s respectively. Whereas A_n for SiC is 0.15 and for GaN is 0.5. GaN has the highest saturation electron velocity among all semiconductor materials, as seen in Figure 4. As electrons in GaN have a large saturation velocity, GaN devices can transmit larger current density.

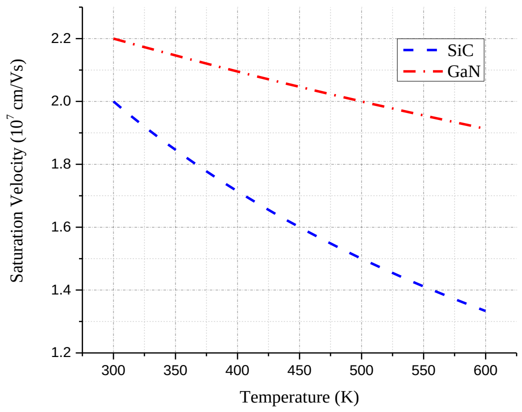


Figure 4. Saturation velocity versus temperature

D. *Thermal Conductivity*

In semiconductor materials, thermal conductivity is a very important parameter and gets a considerable attention from the design engineers. Group IV and Group III-V wide band gap semiconductor material semiconductor materials such as SiC, AlN and GaN are among the materials with high values of thermal conductivity [13]. In comparison with GaN and the traditional Si, SiC has a higher value of thermal conductivity. As a result, it is suited more for high power applications [14]. Equation 4 is used to show thermal conductivity with respect to lattice temperature. Material properties are shown in Table III.

$$\lambda(T_L) = \lambda_{300K}\left(\frac{T_L}{300K}\right)^{\alpha} \quad (4)$$

Where, T_L is lattice temperature, λ (T_L) is thermal conductivity at temperature TL, λ_{300K} is thermal conductivity at room temperature and α is material constant.

Table III Thermal conductivity parameters

Material	A	λ(W/mK)
GaN	-0.43	125
SiC	-1.61	490

SiC has approximately four times greater thermal conductivity than GaN, which is a great advantage. At high temperature operations, heat generated inside the device is very crucial thing and it is better to be dissipated as quickly as possible. This generated heat is directly proportional to the thermal conductivity, greater the value of thermal conductivity more quickly heat will be dissipated. Figure 5 shows the relationship between lattice temperature and thermal conductivity. At room temperature (300K) SiC has value 490 W/mK which is very higher than GaN that has value 125 W/mK. And also at higher temperature SiC has a greater value than GaN at room temperature. This particular property made silicon carbide best option under high temperature operations. To increase thermal conductivity of GaN, it is grown over SiC wafer but still it didn't match with such high values of SiC [14].

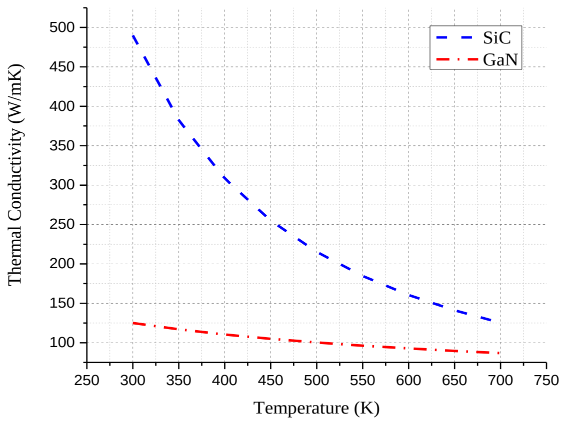


Figure 5. Thermal conductivity versus temperature

3. SiC and GaN Transistor Characteristics at High Temperature

In high frequency power convertors, silicon power MOSFETs have been used extensively due its fast switching. As Si MOSFETs are bounded to comparatively low power applications, SiC and GaN power MOSFETs have gained popularity. SiC and GaN power MOSFETs have larger blocking voltages, larger operating temperature and even larger switching [15]. This portion presents the temperature dependent behavioral using Pspice simulation of a SiC and GaN power MOSFETs.

E. MOSFET modeling and characteritics analysis curves

An equivalent power MOSFET circuit is used for modeling. This model consists of a voltage control current source (as ideal MOSFET), parasitic components, reverse body diode and junction capacitors that vary with voltage. Generally, the Equation 5 and 6 are used to present the MOSFET model.

$$V_{DSsat} = V_{GS} - V_{th} \quad (5)$$

$$I_D = \mu_n C_{OX}\frac{W}{L}\left((V_{GS} - V_{th})V_{DS} - \frac{V^2_{DS}}{2}\right) \quad (6)$$

$$I_D = \frac{\mu_n c_{ox}}{2}\frac{W}{L}(V_{GS} - V_{th})^2\left(1 + \lambda\left(V_{DS} - V_{DSsat}\right)\right) \quad (7)$$

Where, λ is the channel-length modulation parameter, μ_n is the charge-carrier effective mobility, L is the gate length, C_{OX} is the capacitance of the oxide layer, W is the gate width. Equation 6 represents the current in linear region ($V_{DS}<V_{DSsat}$) whereas Equation 7 represents in the saturation region ($V_{DS}\geq V_{DSsat}$). Using the above equations, transfer characteristic has been simulated for GaN and SiC as shown in Figure 6. The n-power law MOSFET model is used for both SiC and GaN modeling [16].

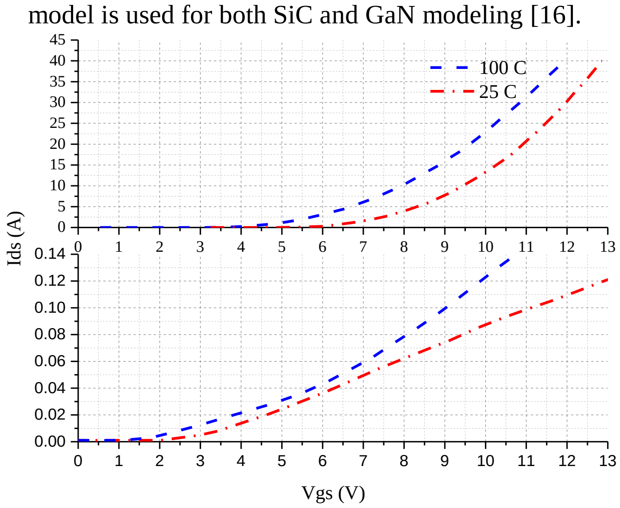
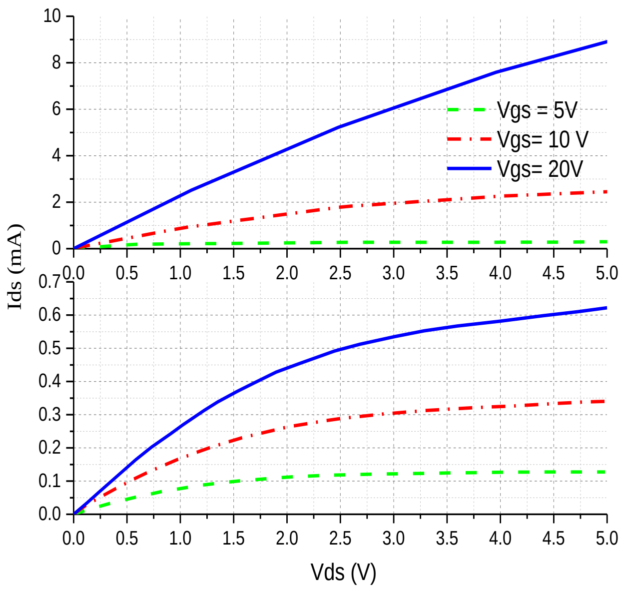


Figure 6. Top plot is for SiC and below is for GaN



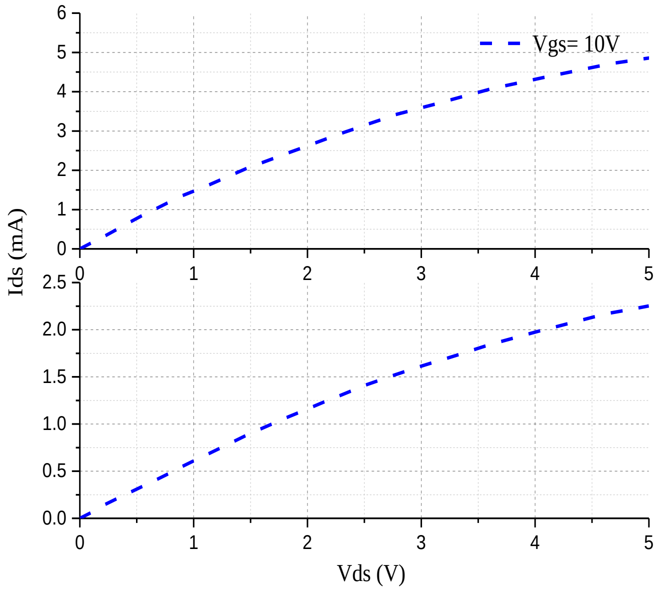


Figure 7. (a) Top plot is for SiC and below is for GaN at 25 °C

(b): Top plot is for SiC and below is for GaN at 200 °C

Figure 6. shows the relation between the gate voltage (Vgs) and drain current (I_{ds}) at two different temperatures i.e. 25 ºC and 100 ºC. The field effect mobility increases with the gate voltage depending upon the provided temperature, up to a certain level. The mobility increases up to two times with the increase in temperature from 25 ºC to 100 ºC. In this model, the voltage controlled current source is described by the below four equations. V_{DSsat} and I_{DSsat} are the saturation voltage and current.

$$V_{DSsat} = K\left(V_{GS} - V_{th}\right)^{m} \tag{8}$$

$$I_{Dsat} = B\left(V_{GS} - V_{th}\right)^{n} \tag{9}$$

$$I_D = I_{Dsat}\left(1+\lambda V_{DS}\right)\left(2-\frac{V_{DS}}{V_{DSsat}}\right)\frac{V_{DS}}{V_{DSsat}} \tag{10}$$

$$I_D = I_{Dsat}\left(1+\lambda V_{DS}\right) \tag{11}$$

All the parameters, including *K*, *B*, *m*, *n* and *λ*, are temperature dependent in this model. There values are calculated from MOSFET model [16]. Similarly, the forward biased characteritics are plotted at different V_{gs} such as 5V, 10V and 20 V at room temperature in Figure 7a.

In Figure 7b. drain voltage and drain current is simulated for V_{gs} 10V at high temperature i.e. 200°C significant rise is observed in the value of current due to increase in the carrier mobility.

4. Conclusion

In this paper behavior of wide band gap semiconductor materials i.e. SiC and GaN has been analyzed at different temperature conditions. At high temperature conditions the physical properties of these materials show a significant change, which must be considered during modeling. It is observed that GaN has very high values of carrier mobility, saturation velocity and energy band gap at high temperature which made it the best option for high current density and high frequency applications. SiC also have competitive values of these parameters with GaN. The leading thermal conductivity of SiC over GaN provides its strong applications in harsh and adverse temperature conditions.

Also the electrical characteristics of the Pspice model have been compared at different temperature ranges. This comparison provides a better overview of these materials for MOSFET analysis. Moreover these materials in comparison with the traditional Si are better in performance at harsh operating conditions. The scope of these materials in the high power electronics switching is very prominent and provide a new gateway in HVDC power converter utilities.

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