

CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

PHYSICS BASED ANALYTICAL MODEL FOR SILICON CARBIDE MESFET FOR  
MICROWAVE FREQUENCY APPLICATIONS

A graduate project submitted in partial fulfillment of the requirements  
for the degree of Masters of Science  
in Electrical Engineering

By

Bodhisattwa Samanta

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The graduate project of Bodhisattwa Samanta is approved:

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Dr. Robert D Connar

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Date

---

Prof. Ramin Roosta

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Date

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Dr. Somnath Chattopadhyay, Chair

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Date

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## ABSTRACT

### PHYSICS BASED ANALYTICAL MODEL FOR SILICON CARBIDE MESFET FOR MICROWAVE FREQUENCY APPLICATIONS

By

Bodhisattwa Samanta

Master of Science in Electrical Engineering

In this paper, we present a physics based analytical modeling and simulation of ion implanted silicon carbide Schottky gate FET. The model has been developed to compute the drain-source current, intrinsic parameters such as, gate capacitances, drain-source resistance and transconductance taking into account of different fabrication parameters such as doping concentration of active channel, doping constant, mobility, the correlation between active channel depth and pinch off voltage and other physical parameters. The physics based analytical model for a non self-aligned SiC MESFET shows different intrinsic and extrinsic parameters reflecting the microwave frequency applications.

## CHAPTER 1

### 1.0 INTRODUCTION

“SiC semiconductor material is having a wide-band hole (~3.3 eV), high breakdown electric field ( $2 - 4 \times 10^6$  V/cm), it is having high thermal conductivity ( $3-5$  W/cm-°C), very high electron saturation velocity ( $2.7 \times 10^7$  cm/s), and a very stable substance bonding. For use in high-temperature, high-power, and high-radiation conditions under which conventional semiconductors cannot perform properly in that case we use Silicon carbide (SiC)-based semiconductor electronic devices and circuits. Silicon carbide can function under such amazing conditions so it can empower critical enhancements to a great deal of applications and frameworks. The aforementioned varies from quite enhanced high voltage switching utilized as a part of public electrical grid for electric distribution and motor drives to additional effective microwave electronics for radar and conveyances to sensors and controls for less dirty burning and more fuel efficient aircraft and vehicles engines” [1-2].

“In the previous ten years, great advancement has been made in the material development and processing of wide band-gap semiconductors, especially SiC and GaN, and high caliber SiC and GaN wafers are presently economically accessible. Both sorts of semiconductors have exceptionally wide band-gap ( $4H-SiC = 3.2$  eV and  $GaN = 3.4$  eV)”[3]. “Additionally,  $4H-SiC$  has extremely high breakdown field, remarkable radiation hardness, and amazing chemical and mechanical rigidity, great thermal conductivity and accordingly are excellent for photo detection in high temperature and high radiation environment conditions” [3]. The Figure 1 and 2 shows the breakdown voltage and thermal conductivity of distinctive semiconductor materials.” Because of the wide band-gap of SiC and GaN, the leakage current could be orders of magnitude lower than the leakage current of Si identifiers, making SiC and GaN great candidates for high sensitivity obvious visually blind UV detection. GaN has the advantage of the accessibility of heterostructures, which permits deciding cutoff wavelength in the UV range by utilizing AlGaN with distinctive Al percentage. It in this manner includes great adaptability in detector design and relieves or takes out the requirements of optical filters. SiC, in any case, has much better material development contrasted with GaN material. Moreover, SiC substrate and epi-development innovations have advanced to this level as to permit the manufacture of numerous distinctive sorts of SiC photo detectors with desired characteristics. SiC UV p-i-n photodiodes have as of recently been manufactured and are economically accessible. SiC avalanche photodiodes with very high gain and level abundance noise have been showed” [4]. “SiC based power MESFET has pulled in awe inspiring attention for provisions in high power and repeat electronic mechanisms[4]. The wide band-gap makes it possible to use SiC for uncommonly high temperature operation, up to  $600$  °C contemplated to  $150$  °C for Silicon [5]”. “SiC instruments furthermore have been showed to have level shortcoming to high radiation estimations up to  $100$  megarad [6]. A high breakdown voltage  $4H-SiC$  Schottky diode with edge termination structure was demonstrated with  $5$  kV breakdown voltage [7,8]”. “ $6H$ -and  $4H-SiC$  Schottky block diodes with breakdown voltages of  $1000$  V and  $1400$  V and flow densities  $100$  A/cm<sup>2</sup> also  $700$  A/cm<sup>2</sup> independently were accounted for many research groups”[9,10]. “The creation of high voltage  $6H-SiC$  Schottky hindrance diodes and closely watched breakdown voltage surpassing  $400$  V has been accounted for I-V qualities of submicron  $4H-SiC$  MESFETs

have been examined by a few research gathers” [11]. “Units have been displayed with a RF yield control thickness of 2.8 W/mm at 1.8 GHz. This power thickness is three times higher than equal GaAs units with high quality and lower development losses at working temperature [12]. Increased power SiC MESFET units made by K. P. Hilton, et.al. were fit to control yield of 6.8 W and 16 W from a solitary three device chip at a frequency of 4 GHz [13]. "Sband 4H-SiC MESFETs for microwave control application have demonstrated high power densities in the extent of 5.6 W/mm and 36% power-added efficiency (PAE) and CW force of 80 W". This exhibits the usefulness of SiC MESFETs and their circuits in linear transmitters for business and military use” [14].

"Baliga, et. al. have reported a voltage 6h-Sic Mesfet made with ion implantation process and a novel especially asymmetrical source to gate channel structure was made, which is fit for forward blocking voltage of 450 V with a gate voltage of -20 V [15]. Sic metal semiconductor field impact transistors (Mesfets) are fabricated with more than 60 W of yield power at 450 Mhz from single 21.6 mm gate devices(2.9 W/mm) and 27 W of yield power at 3 Ghz from single 14.4 mm". The unfathomable unit exhibition has been credited to the upgraded substrate and epitaxial films esteem, redesigned apparatus thermal administration, and redesigned manufacturing advances. Sic Mesfets are well known contraptions for power amplifier design in lifted power and uplifted temperature procurements in perspective of Sic's pervasive grounds, for instance increased breakdown voltage, high thermal conductivity, and extreme electron velocity [16]. The development of Sic gadgets in wireless engineering gives the motivation of investigating in the zone of nonlinear showing, which is helpful for gadget presentation examination in composing microwave circuits and depicting the apparatus assembling strategy.

Fig 1. Breakdown voltages for different semiconductors materials.

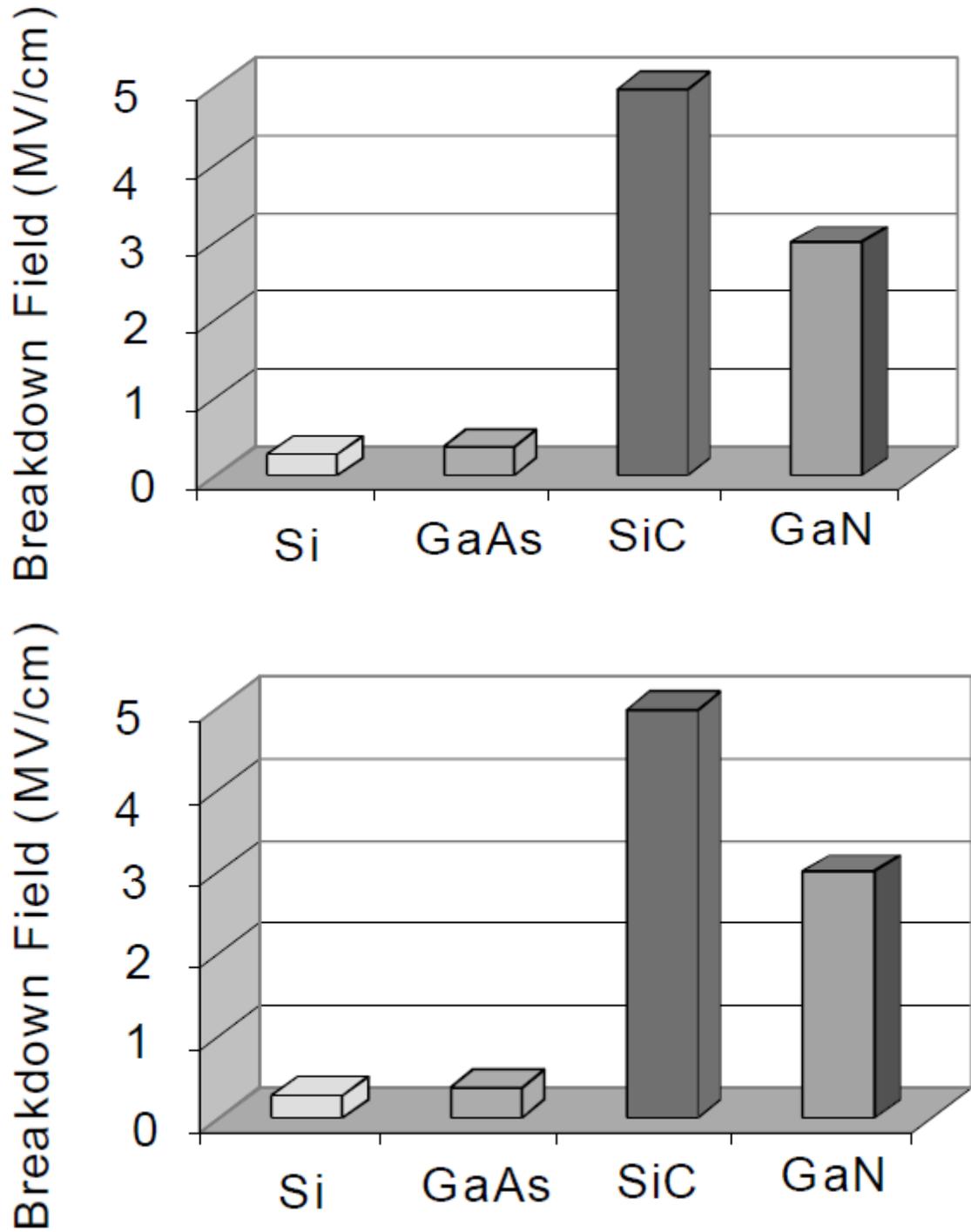


Fig 2. Thermal conductivity for different semiconductors materials.

“Silicon carbide (SiC) is a standout near the most making a guarantee to alternatives to silicon (Si) for force semiconductor mechanisms in view of its prevalent material angles. Case in point, its high breakdown electric field realizes exceptionally high voltage-blocking capability with a much lower on-safety if contrasted and Si, while its immense band-gap energy prompts higher temperature operation limit, higher radiation hardness, and modestly higher thermal conductivity – a critical benefit the extent that power dispersal. With quick development of portable correspondences represented by compact telephones, further fabricates in the yield of high frequency control transistors for the base stations are wanted. Also, in the fields of satellite correspondences and radar, yield of high power transistors restoring electron tubes for instance TWTs and magnetrons is used for size reducing, weight decrease, and increase of transmitter life. As a transistor satisfying all needs, the metal semiconductor field transistor (MESFET) indigent upon silicon carbide (SiC) has been attracting thought. SiC is prevalent in material traits for instance the electric breakdown field and thermal conductivity and is wanted theoretically to give elevated power thickness as a heightened recurrence transistor.

Power Added Efficiency (PAE) is a better figure of merit as it incorporates the transistor power gain. As the power gain ( $P_{out}/P_{in}$ ) increases, the difference between the power added efficiency and the drain efficiency becomes small. The maximum output power point for the SiC MESFET device was under Class A operation. At a drain bias of V and mA (50%), with the device tuned for maximum power, the device had a peak output power of 30.5 dBm (3.37 W/mm) and a 3 dB compression output power of 30.2 dBm (3.1W/mm). The device had a power added efficiency of 38.4% at this bias point. The best efficiency for this device was under Class B operation, with the device tuned for maximum efficiency. The peak efficiency occurred at a bias of V and mA (5%), where the device exhibited 65.7% power added efficiency. The device had 28.4-dBm output power (2.12 W/mm) at the point of peak efficiency, which was also the 3 dB compression points. At this bias point, the device had 28.8-dBm maximum output power (2.27W/mm), but efficiency decreased to 61.3% as the device went into deep compression. It should be noted that the high drain bias of 50 V for the large signal measurements requires a very high gate-drain breakdown voltage of over 100 V. The highest power density and power added efficiency is reported to SiC MESFET as is two times larger than GaAs MESFET. The low frequency noise research was conducted on SiC Metal-Semiconductor Field Effect Transistors (MESFETs). The least complex SiC power device is the Schottky rectifier, which consists of an N+ doped substrate with backside ohmic contact, a lightly doped epitaxial drift layer and a topside Schottky contact with a high-resistivity edge termination. The Schottky diode is fabricated by evaporating a high work function metal, such as titanium, nickel, or gold, onto the epitaxial layer to form the Schottky contact and by depositing an ohmic contact metal onto the back of the N+ substrate”[17]. “The order of these depositions may be reversed to accommodate annealing of the ohmic contact. The process is self-aligned to the Schottky contact because the Schottky metal acts as a mask

preventing damage under the contact. The most important device properties are high reverse breakdown voltage and low forward resistance, which produces a high forward current density.”[17]

### **1.1 Optoelectronic Devices based on SiC:**

During the past few years more time has been spent in development and research in MESFET. Due to this research OPFETs that is optically controlled field effect transistors got lot of attention due because of the advantages in the high speed optical switching and also high frequency optical operation in modulation/demodulation applications. Lot of theoretical and experiments have been done which shows varying dynamic properties in gate FETs, at the time when light beam strikes the transistor gate it causes change in the potential of gate junction equivalent to the threshold voltage. To understand the characteristic and operation of OPFET theoretical and experimental results are conducted continuously and the results are reported exploring the illumination effect for various biases. The optically controlled MESFET (or OPFET) is important as it can be used as a “photo detector” and “pre-amplifier, rf. switch and tuner, etc”. Many techniques are used to improve the terminal properties of the optically controlled gate FET, are:

1. Photo-induced potential across the Schottky barrier,
2. Carriers which are photo generated below the gate
3. How photo conductivity changes the parameters in the source, gate and drain regions and the width of depletion region of gate also changes.

Moreover, when positive potential is seen at depletion region of n-type region and substrate shows the effect of channel width modulation on the improvement of drain current of the device [18]. Lot of enthusiasm is observed in studying and modeling of OPFET and it is fabricated where Schottky gate is used generally. “These OPFET’s are expected to emerge as promising detectors for use in integrated optoelectronic circuits. A number of theoretical and experimental investigations on the effect of illumination on MESFET structures have been reported. Preliminary investigations reveal that photo response of illuminated MESFET is due to the optically generated carriers, which increase the conductivity of the channel and the photo voltage developed across the Schottky barrier, which affects the applied reverse voltage on the gate. Simple models have been developed by several workers in order to explain the results of experimental investigations on the effect of illumination on commercially available SiC MESFET’s”[18]. Large signal parameters are also observed for OPFETs. “A simple yet fairly accurate model, which takes into account, all the important physical phenomena involved in an illuminated MESFET need to be considered for this purpose”[18].

OPFET which uses SiC are used for lot of important applications such as it used as transducer for optical communication, “integrated optics, and optical computer”. “B.B.Paland, S. N. Chattopadhyay studied the SiC OPFET Characteristics Considering the Effect of Gate Depletion with Modulation Due to Incident Radiation”. “It was found that the photovoltaic effect is important because it develops a forward voltage across the metal-semiconductor junction, which increases with the increase in radiation intensity. This photo voltage modulates the depletion region width below the gate, which, in turn, modulates the channel width. The photo voltage thus is expected to increase the drain-source current. It will reduce the threshold voltage in the normally OFF devices and increase in the normally ON devices. At higher flux density and trap density, the threshold voltage shows nonlinear effect at lower value of implanted dose, which is mainly due to the recombination term. The device is pinched off at a higher drain-source voltage compared to the photo generation case only. Some experiments have shown that the FET dc characteristics may alter with illumination and that FET oscillators may be tuned by varying the intensity of the light falling on the active region of the device. Also, some authors have recently reported high-speed optical detection with SiC MESFET’S” [19].

Spectral response of SiC photo diode is seen to be 210 –380 nm. Silicon Carbide Photo diodes are not sensitive to UV radiation in the region outside region of spectral response. Previously we usually used solar rejection filters but now we can use this photo diode for observing UV spectrum. SiC photo detectors are used for UV exposures for long time this usefulness of withstanding long exposures of UV light makes it extremely durable and can be used for lot of application specially UV applications. “Intrinsic spectral response is limited to the range of 200 - 400nm and no additional blocking of unwanted visual and IR-range of radiation is necessary. SiC photodiodes are proven for outstanding long-term stability under high doses of UV –C-radiation. These devices also have an excellent temperature stability, can operate at 150°C. SiC photodiode is offered with radiation hard standard space approved filters for narrow band such as UV-A, UV-B and UV-C” [19].

“There has been considerable work done on the development of silicon based optoelectronic integrated circuits (OEIC’s). Mature silicon-processing technology, including micromachining techniques, can be used to fabricate complex optical structures such as micro optical devices and hybrid optoelectronics. The silicon based OPFET promises excellent compatibility with current silicon IC technology requiring the same or similar low-cost and reliable manufacturing techniques of monolithic silicon-based OEICs. The ion implantation induced defects in a silicon substrate have been characterized by measuring the bulk generation lifetime of MOS capacitor and experiments have been conducted to study the dependence of substrate dopant species (phosphorous and boron) on defect formations. I-V characteristics of ion implanted solar cell devices at optical illumination have shown the efficiency in the range of 0.01%. Phosphorous ion

implantation not only results in the transition of the crystalline fullerenes to amorphous material phase, but also produces a significant defect level. An effective loss of photo-generated carriers due to the ion implantation process induced defects in the active channel region of OPFET is a major issue of degradation of quantum efficiency, sensitivity, etc. The channel current obtained from the diffusion and ion implanted OPFET devices are studied and both currents under dark and optical illumination conditions are compared to realize the process-induced defects as major problem for optoelectronics device. Use of direct control of microwave semiconductor devices for optical injection locking, phase shifting, signal distribution and optoelectronic actuator has the potential to enhance the performance of future space borne phased array systems and military and commercial aviation. Previously, several authors have experimentally investigated the effect of light on dc and microwave characteristics of MESFET. Their investigations show that these changes in the characteristics are due to photoconductivity and photovoltaic effects. Further, an analytical study, by the authors taking into consideration material properties of hetrostructures showed that the hetro-structures have a higher sensitivity to optical illumination” [20].

Lot of researchers have made use of MESFET as an optical detector and control device in microwave applications. “De Salles has performed a thorough experimental and theoretical characterization on the MESFET emphasizing the photovoltaic effect, which can be used to increase the drain current and change the gate capacitance. His analysis is concentrated on the active region of the device; photocurrent in the substrate is ignored. Darling has developed a perturbation analysis to account for the photoconductive effect under low-level illumination. Simons derived analytical expressions for I-V characteristics of different types of FET configurations under optical illumination on the devices. He also computed variations in FET small signal parameters such as transconductance, channel conductance with illumination and compared with the commercially available OPFETs” [21].

## CHAPTER 2

### 2. SiC Material Information

SiC Carbide Crystal information is explained below:-

Silicon Carbide Crystals

- SiC is Extremely hard.
- “Crystalline silicon carbide occurs in many different crystallographic configurations known as polytypes”

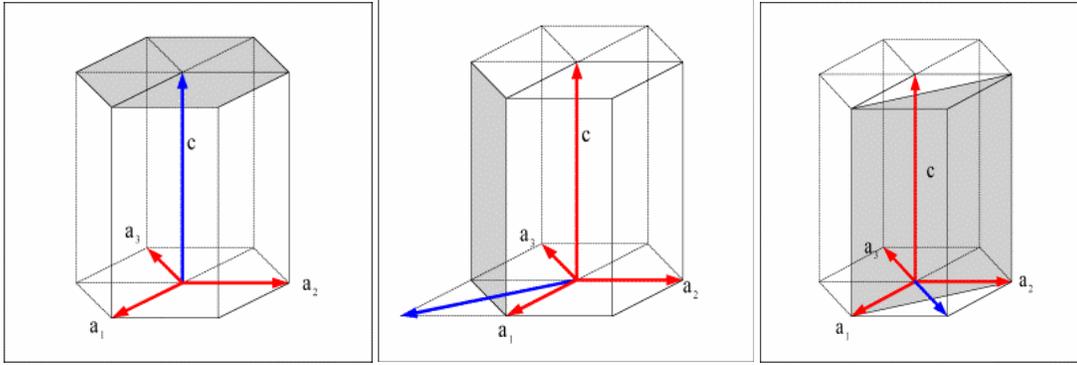
Classical Notation:

- “ $\beta$ -SiC: Cubic structure (3C)”
- “ $\alpha$ -SiC: All other polytypes (hexagonal, rhombohedral, most common are 6H and 4H)”
- “Ramsdell Notation: <number><letter>, i.e. 6H”
- The number of planes are stacked before repeating; which this signifies the polytype
- “The letter is the crystal structure, i.e. C is cubic, H is hexagonal, R is rhombohedral”
- “Common polytypes include: 3C, 2H, 4H, 6H, 8H, 9R, 10H, 14H, 15R, 19R, 20H, 21H and 24R.”

Silicon Carbide structure is explained below, it has Hexagonal Structure which is shown in figure 4. ,figure 5. ,figure 6.[22-25]

Hexagonal Structure

- Hexagonal structure is common because “4H and 6H are the polytypes most often used for devices”
- “Hexagonal structure has four axes:  $a_1$ ,  $a_2$ ,  $a_3$  ( $120^\circ$  apart) and a perpendicular c-axis”
- Most important planes and directions:



**(0001) plane, [0001] direction    (1100) plane, [1100] direction    (1120) plane, [1120] direction**

Figure 3.

Figure 4.

Figure 5.

Another type of structure of Silicon Carbide is explained below and shown in figure 6.

Polytypism

- By changing the three layers mentioned with different periods and orders, polytypes are formed.
- In SiC, however, the “spheres are replaced by the SiC tetrahedral”
- “Infinite polytypes are possible”
- “Over 200 polytypes have been observed experimentally”
- “Polytypes with sequences as long as 594 layers have been observed!”[22-25]

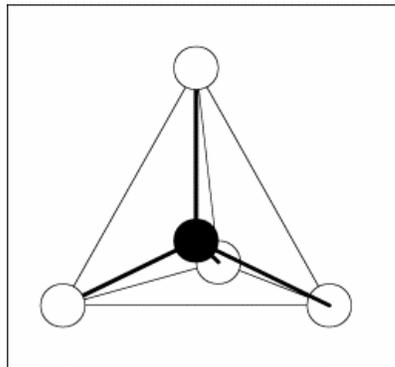


Fig6. SiC Tetrahedron

Polytypism is further explained and shown in figure 7, figure 8, figure 9 and figure 10.

Polytypism – Percentage Hexagonal

- “SiC polytypes have local hexagonal and cubic environments”
- “Local hexagonal environment denoted by  $h$ ”
- “Local cubic environment denoted by  $k$ ”

- “3C – 0% Hexagonal (pure cubic)”
- “6H – 33% Hexagonal”
- “4H – 50% Hexagonal”
- “2H – 100% (pure) Hexagonal” [22-25]

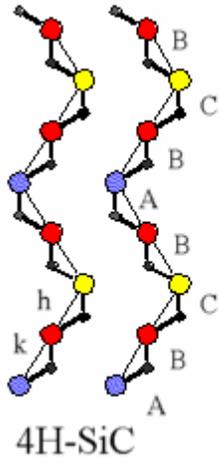


Figure 7

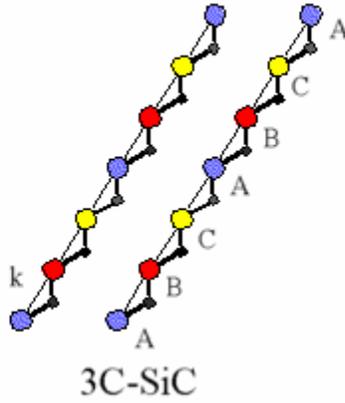


Figure 8

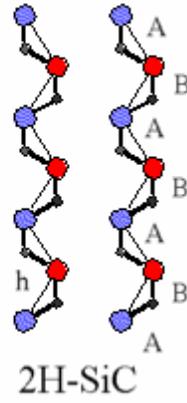


Figure 9

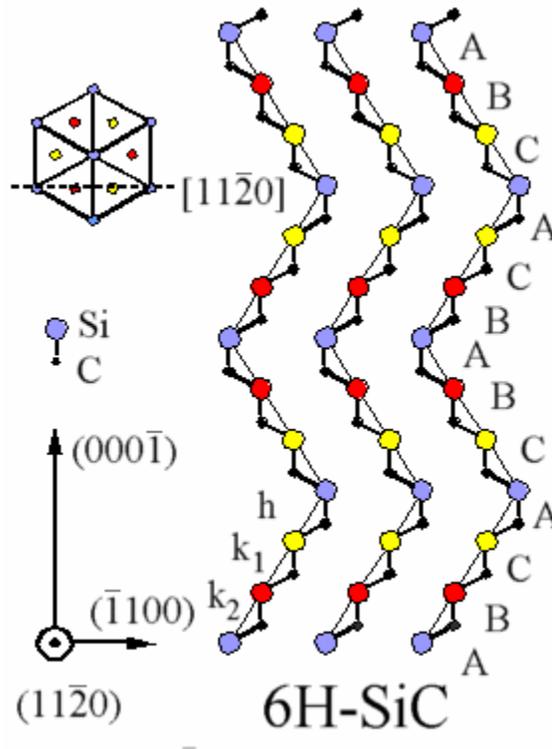


Figure 10.

## SiC Growth

The SiC situation suffers from the very same thing that makes it so good. The bond is very strong and so all processes go on at very high temperature. The growth of Silicon Carbide is explained below. [22-25]

### Introduction to SiC Growth

- Silicon carbide can be grown in bulk and epitaxially

#### Bulk Growth:

- “Physical Vapor Transport (PVT)” or “Modified Lely Method”
- “High Temperature Chemical Vapor Deposition (HTCVD)”

#### Epitaxial Growth:

- “Most SiC devices require an epi-layer”
- “Usually homoepitaxial”
- “Most commonly done with CVD”
- “SiC substrates are often used for GaN” [22-25]

There are many methods to grow Silicon Carbide, some of them are shown below, Lely Growth Method is explained below and shown fig 11.

#### Lely Growth Method

- Invented by “J.A. Lely in 1955 (Phillips Labs, Germany)”
- “Condensed” version the Acheson process
- “Powdered SiC sublimed on the walls of a growth cavity”
- “More efficient than Acheson”
- Some will result very high quality crystals
- Low yield so no polytype control [22-25]

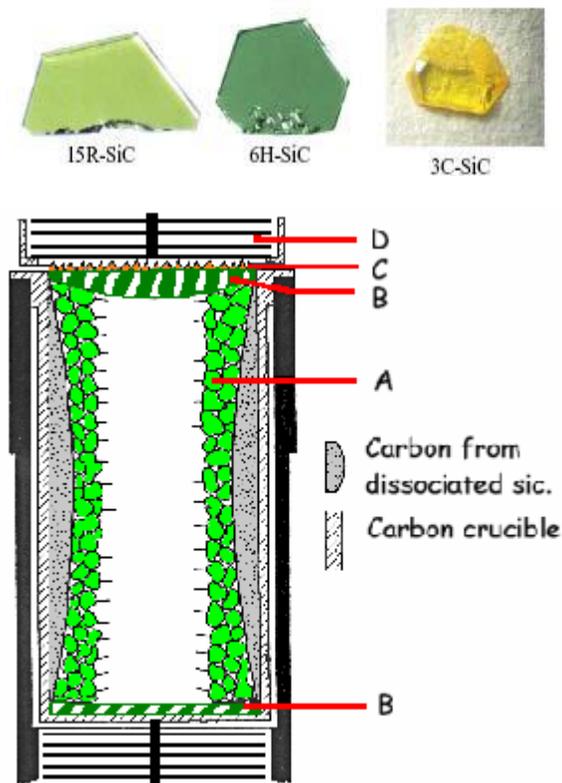


Figure 11.

The above method is further modified as below and shown in figure 12.

#### “Modified Lely” Growth Method

- “Argon environment; pressures from  $10^{-4}$  to 760 torr”
- “Heated to about 1800-2200°C, powdered silicon sublimes”
- “Temperature gradient exists between powder and seed crystal which forces the sublimed SiC to move to the seed crystal”
- “SiC condenses on the seed and the crystal is formed”

- “Typical growth rates: 0.5-5 mm/hr” [22-25]

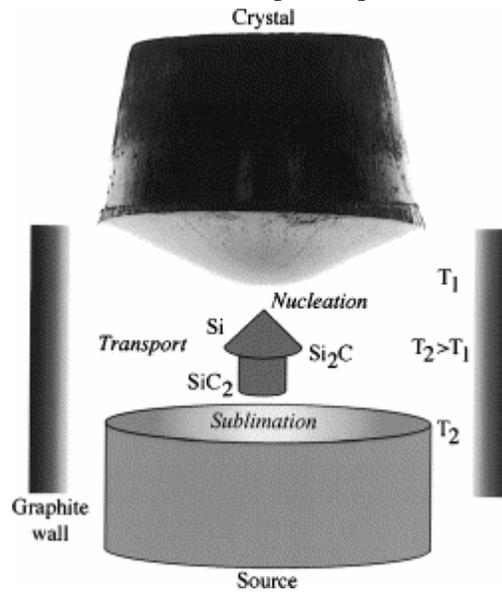


Figure 12.

High temperature CVD method to grow Silicon Carbide is shown below, it is also shown in figure 13.

#### High Temperature CVD

- “Invented in 1996 by Kordina”
- Alternative method for bulk growth
- “Three zones: entrance, sublimation and growth zones”
- “Three gases: silane, propane, and helium (carrier)”
- “Gasses flow through the entrance zone, sublime to form various atoms: Si, Si<sub>2</sub>C, SiC<sub>2</sub>”
- “Temperatures range from 2200-2300°C”
- “Coaxial entrance tube is used to prevent nucleation on the walls”
- “Max growth rates of about 0.8 to 1.0 mm/hr [22-25]”

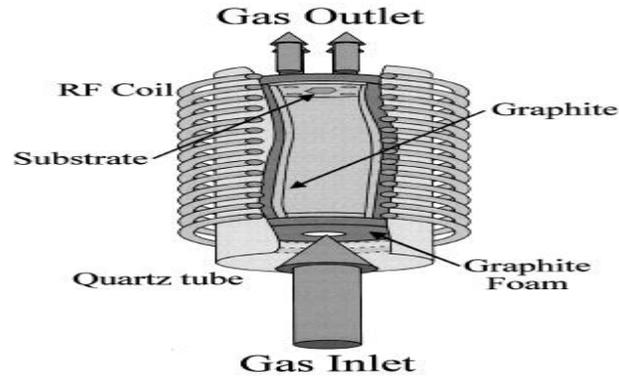


Figure 13.

### Epitaxial Growth

- Quality growth of epitaxial layers is as important as bulk growth because it is required and used for most electronic devices
- Layers can be grown on “AlN, TiC, Si, sapphire, and bulk SiC”
- “Bulk SiC is the best substrate for growth of epi-layers used in device fabrication”
- “Chemical Vapor Deposition (CVD) is the preferred method of epitaxial growth in industry”
- “Most popular type of CVD is known as “Hot Wall” CVD, solves problem of energy loss on side walls”
- Other methods to grow epitaxially are “Sublimation Epitaxy and Liquid Phase Epitaxy” [22-25]

Chemical vapour deposition is another method to Silicon Carbide growth, it is also shown in figure 14.

### Chemical Vapor Deposition

- Typical supply gases are “silane and propane (or other hydrocarbon), hydrogen carrier”
- Substrate temperatures are generally above 1300°C
- “Typically, gas flows at about 30 sccm through a hot wall made of graphite”
- “Growth rates of 15-20  $\mu\text{m/hr}$  achieved” [22-25]

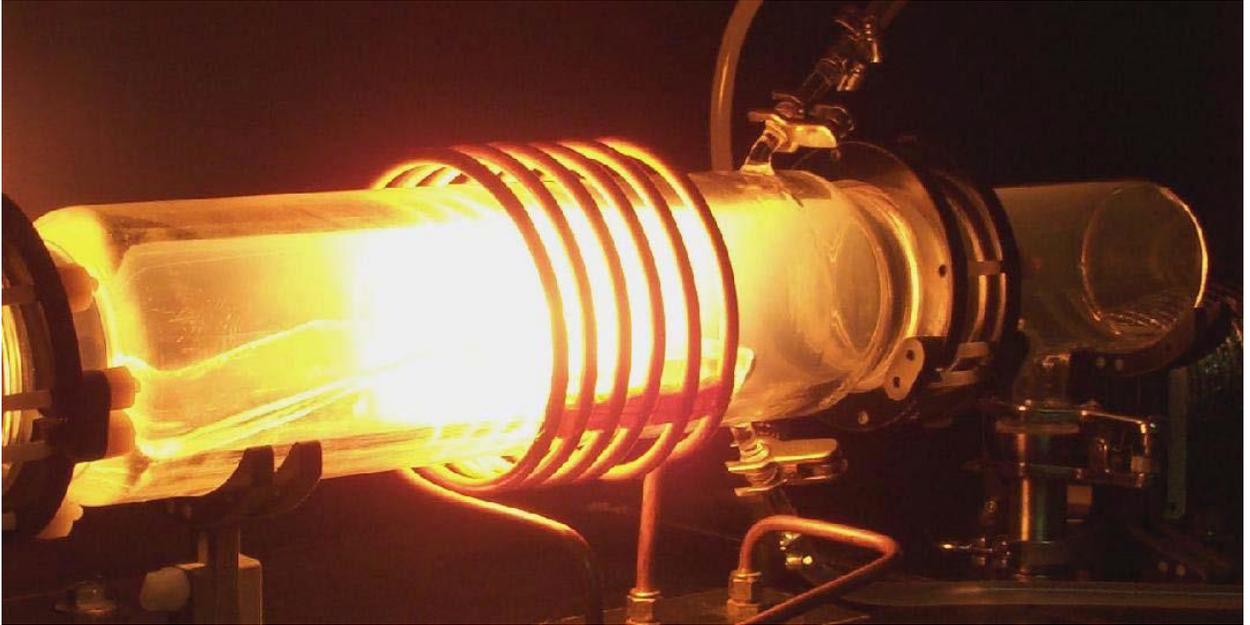


Figure 14.CVD

## 2.1 Defects

Defects is the major limiting factor in the growth of silicon carbide because they are often used to determine to the formation of electrical devices and then the defects appear.

Several types of defects affect SiC:

- “Micropipes”
- “Hexagonal Voids”
- “Closed core screw dislocations”
- “Low-angle boundaries”
- “Stacking faults/transformations” [22-25]

Micropipes are the most common defect of Silicon Carbide, it is shown in figure 15.

Micropipes

- Screws are dislocated which form along the c-axis
- “Diameter on the order of 1 micron”
- Require a “ KOH etch and Nomarski contrast”
- Propagate generally from a bulk to epitaxial layer
- “Micropipes are the most deleterious defect to electrical devices”
- Act like tiny wires which create regions of higher conductivity thus allowing current to flow and causes shorting of devices
- It decreases lifetime with increase “off” current and decreases reverse bias breakdown voltages [22-25]

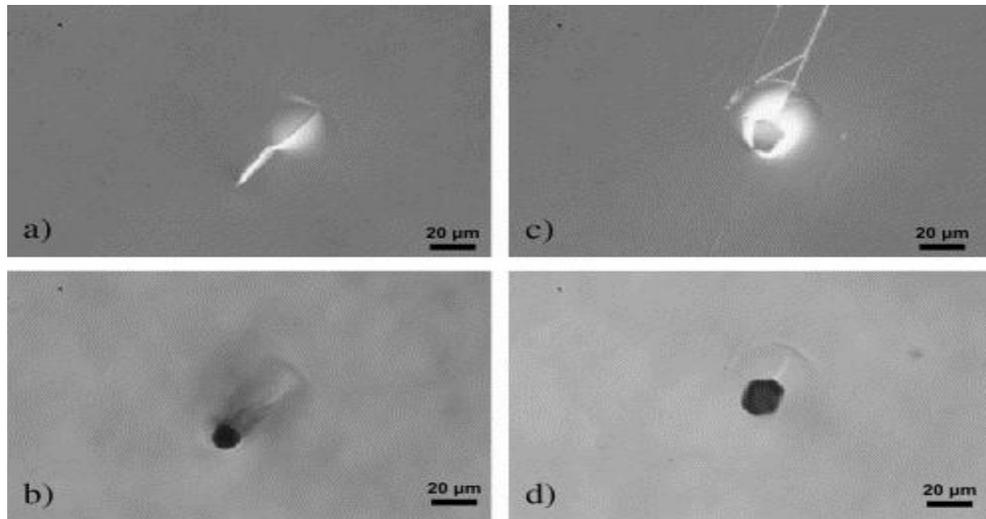


Figure 15. Micropipe Defects

Low angle grain boundary is also a Silicon Carbide defect as explained below and shown in figure 16.

Low Angle Grain Boundaries

- “Another type of void in the substrate which propagate radially inward”
- “Result from poor processing conditions; has been eliminated through process optimization”.
- “Electrical effects do not appear to be problematic” [22-25]

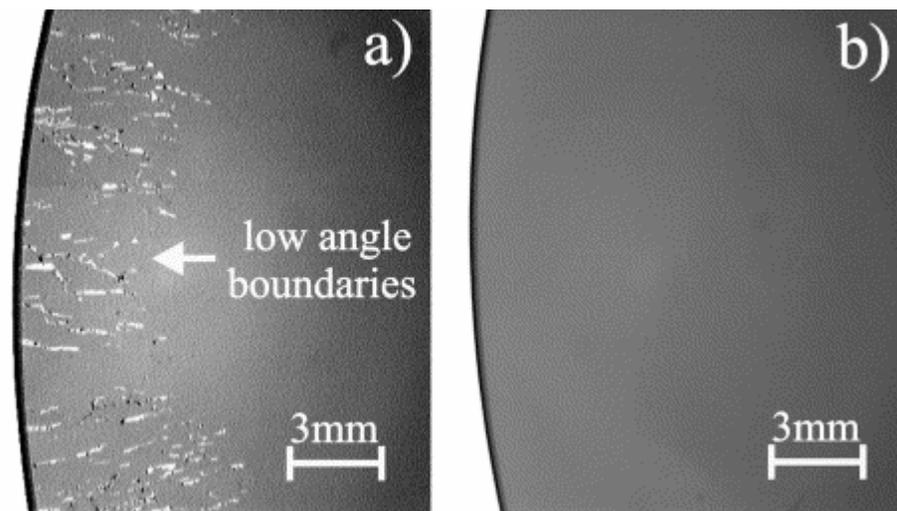


Fig 16. Low angle boundary defects

## 2.2 Reason to use SiC:

- When we require to use high temperature and power we prefer and make use of Silicon Carbide.

- SiC is in a unique position due to its ability to grow SiO<sub>2</sub>
- Its usefulness has been known for decades, but due to absence of high quality material development of SiC devices are delayed
- “Substrate diameters have been steadily increasing since the commercial introduction of substrates in 1991”
- Micropipes defects have been reduced in the last decade
- “Recently, as many as 15 companies have entered the market, to attempt to compete with the SiC giant, Cree”
- “Commercial devices are available, but their widespread use will depend on the ability of growers to make large, inexpensive, defect free materials available” [22-25].

### 2.3 Radiation Hardness of SiC Material

“The impact of the traps actuated by irradiation on their attributes was centered. In the SBD's re-enactment, traps in the material make the forward current and reverse current diminished. In the MESFET's simulation, we discovered that it can withstand more traps in the material instigated by irradiation because of the higher impurity concentration in the channel. The Ni/4H-SiC Schottky barrier diodes (SBDs) and TLM (Transfer Length Method) test examples of Ni/4H-SiC ohmic contacts were created, and lighted with 1MeV electrons up to a measurements of  $3.43 \times 10^{14} \text{ e/cm}^2$ . After radiation, the forward currents of the SBDs at 2v diminished by about 50%, and the opposite currents at -200v expanded by less than 30%. Schottky barrier height ( $\phi_B$ ) of the Ni/4H-SiC SBD expanded from 1.20eV to 1.21eV under 0v light inclination, and diminished from 1.25eV to 1.19eV under -30v bias. The degrading of  $\phi_B$  could be illustrated by the variety of interface states of Schottky contacts. The on-state resistance ( $R_s$ ) and the opposite current expanded with the dosage, which could be credited to the radiation surrenders in mass material. The particular contact safety ( $\rho_c$ ) of the Ni/SiC ohmic contact expanded from  $5.11 \times 10^{-5} \Omega \text{ cm}^2$  to  $2.97 \times 10^{-4} \Omega \text{ cm}^2$ . The Ni/4H-SiC Schottky barrier diodes (SBDs) were illuminated with the  $^{60}\text{Co}$  gamma-ray source to the collected measurement of 1Mrad(Si). 0v and -30v predisposition voltages were connected with the SBDs throughout irradiation. After 1Mrad(Si) radiation, Schottky barrier diode element of the Ni/4H-SiC SBDs under distinctive inclination voltage basically continue as same values, and minority bearer lifetime of the epitaxial layer additionally has no degradation. The opposite current diminishes after radiation, which might be illustrated by the negative surface charge increment. The effects show radiation predisposition voltage has small impact of gamma-ray on the Ni/4H-SiC SBD. Through testing and simulating information, we discovered after radiation with 1MeV electrons up to a measurements of  $3.43 \times 10^{14} \text{ e/cm}^2$ , the Schottky obstruction stature updated somewhat and recuperated with annealing at room temperature for a week. In any case  $R_s$  didn't recuperate a week later. 1Mrad (Si) gamma-ray radiation barely change the Ni/4H-SiC SBD's characters.” [24]

### 2.3.1 Impact of Ionizing Radiation on 4H-SiC Devices

“Electronic devices, in light of current semiconductor technologies and managing in radiation rich environment, endure degradation of their performance due to radiation introduction. Silicon carbide (SiC) provides an interchange solution as a radiation hard material, on account of its wide bandgap and higher atomic displacement energies, for devices expected for radiation environment provisions. Be that as it may, the radiation tolerance and dependability of SiC-based mechanisms should be comprehended by testing mechanisms under regulated radiation situations. The aforementioned sorts of studies have been performed previously on diodes and MESFETs, but multilayer devices for example bipolar junction transistors (BJT) have not yet been studied.

In this thesis, SiC material, BJTs fabricated from SiC, and various dielectrics for SiC passivation are studied by exposure to high energy ion beams with selected energies and fluencies. The studies reveal that the implantation induced crystal damage in SiC material can be partly recovered at relatively low temperatures, for damage levels much lower than needed for amorphization. The implantation experiments performed on BJTs in the bulk of devices show that the degradation in device performance produced by low dose ion implantations can be recovered at 420 °C, however, higher doses produce more resistant damage. Ion induced damage at the interface of passivation layer and SiC in BJT has also been examined in this thesis. It is found that damaging of the interface by ionizing radiation reduces the current gain as well. However, for this type of damage, annealing at low temperatures further reduces the gain.

Silicon dioxide (SiO<sub>2</sub>) is today the dielectric material most often used for gate dielectric or passivation layers, also for SiC. However, in this thesis several alternate passive materials are investigated, such as, AlN, Al<sub>2</sub>O<sub>3</sub> and Ta<sub>2</sub>O<sub>5</sub>. These materials are deposited by atomic layer deposition (ALD) both as single layers and in stacks, combining several different layers. Al<sub>2</sub>O<sub>3</sub> is further investigated with respect to thermal stability and radiation hardness. It is observed that high temperature treatment of Al<sub>2</sub>O<sub>3</sub> can substantially improve the performance of the dielectric film. A radiation hardness study furthermore reveals that Al<sub>2</sub>O<sub>3</sub> is more resistant to ionizing radiation than currently used SiO<sub>2</sub> and it is a suitable candidate for devices in radiation rich applications.”[25]

### 2.4 Applications:

“As noted earlier, there are many different areas of application to which SiC can apply. The most obvious application of these devices is in engines, where extremely high temperatures can cause most other semiconductor devices to fail. A more subtle application of Silicon Carbide is for the manufacturing of crucibles, and to replace the quartz wafer carrying racks used in semiconductor manufacturing. In fact, the quartz wafer carrying racks usually last only about one week before it needs to be replaced, whereas the SiC wafer rack can last a couple of years” [26].

“Again, due to SiC’s great tolerance to heat and outstanding corrosion resistance in certain chemical environments, as well as its strength make it a perfect candidate for these

applications. Here is a list of what was found about the current SiC applications to name a few: Ballistic armor tiles for personnel, vehicle and aircraft applications, bearings, tooling for semiconductor processing applications including focus rings, susceptors, and gas distribution plates, polishing plates for semiconductor wafers, highly reflective mirrors for lasers, wear components for paper making machines, small quantity special seal faces for the chemical processing industry, and the list goes on. Silicon Carbide replaces metals, tungsten carbide and other ceramic materials, such as aluminum oxide, for these applications” [27-28].

## CHAPTER 3

### 3. SCHOTTKY DIODE

“Schottky diode is a semiconductor diode with a level advance voltage drop and an exceptionally quick switching activity. At the point when current passes through the diode there is a small voltage drop over the diode electrodes. A conventional silicon p-n junction diode has a built in voltage between 0.6-0.7 V. However a Schottky diode has a built in voltage between 0.15-0.45V. A metal-semiconductor junction is formed by metal and semiconductor creating a Schottky junction. The conventional metals used are molybdenum, platinum, chromium or tungsten and the semiconductor are ideal Schottky metals for n-type silicon. The metal side is considered as the anode and the n-semiconductor functions is defined as the cathode of the diode. The quick voltage drop can give higher switching speed and better proficiency in device performance”. The structure of Schottky diode is showed in figure 17.

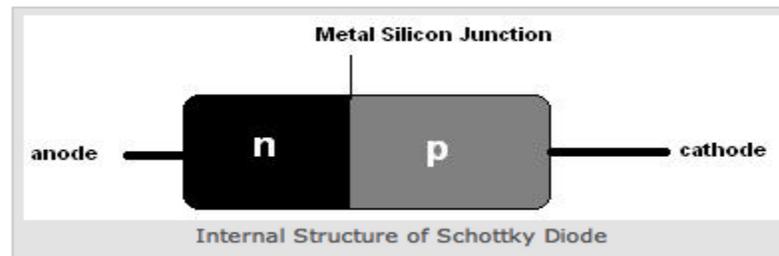


Figure 17. Internal structure of Schottky Diode

“The most critical contrast between the p-n and Schottky diode is opposite recuperation time, when the diode switches from non-leading to directing state and vice versa. Figure 17. shows the inside structure of Schottky Diode. Schottky diodes don't have a recuperation time, as there is nothing to recuperate, as there is no charge bearer consumption locale at the intersection. Schottky diode is a lion's share bearer semiconductor device. Assuming that the semiconductor is doped with n-sort, just the n-sort bearers play a noteworthy part in standard operation of the mechanism. The greater part bearers are rapidly ended up being moving electrons. Along these lines no moderate, irregular recombination of n-sort and p-sort bearers is included, so this diode can stop conduction speedier than a p-n rectifier diode. This property permits a more diminutive apparatus range, which likewise makes a speedier move and subsequently Schottky diodes are utilized as a part of switch-mode control converters. The circuit can manage at frequencies in the reach 200KHz to 2 MHz.

Schottky diodes the main part of RF indicators, which can manage upto 50GHz”[23-36].



Figure 18. Schottky diode Symbol

“Schottky diode is utilized as a high voltage or power rectifier. The Schottky diode rectifier has numerous useful advantages over different sorts of diodes. Figure 18 shows the image of Schottky diode. The low forward voltage drop offered by Schottky diode power rectifiers is a noteworthy application in numerous occasions. It diminishes the power losses ordinarily acquired in the rectifier and different diodes utilized within the power supply. With standard silicon diodes offering the principle alternative, their turn on voltage is around 0.6 to 0.7 V, Schottky diode rectifiers having a turn on voltage of around 0.2 to 0.3V, there is a noteworthy power saving to be gained. The resistance of the material will present losses, and the voltage drop over the diode will build the current. The losses of the Schottky diode rectifier will be much less when compared to that of the silicon rectifier. Schottky diode rectifiers have a much higher reverse leakage current than standard PN junction silicon diodes. The most extreme junction temperature of a Schottky diode rectifier is typically restricted to the extent 125°C to 175°C. Schottky diode rectifiers have a restricted reverse voltage capability” [27].

### 3.1 SILICON CARBIDE SCHOTTKY DIODE:

“There is major benefits using Schottky diodes constructed from Silicon Carbide have a very low reverse leakage current when compared to a Silicon Schottky diode. Currently from last few years, these diodes are available in variants up to 1700 V. Thermal conductivity of Silicon carbide is very high and it has high temperature but it has no real effect on its switching and thermal characteristics [28]. When it is packed in proper way, it is possible to have operating temperatures of over 500 K, which helps in passive radiation cooling used in aerospace applications. SiC MESFET’s are wide energy gap devices, with high-saturated electron velocity and high melting point”. SiC basic MESFET structure is shown in figure 19[29].

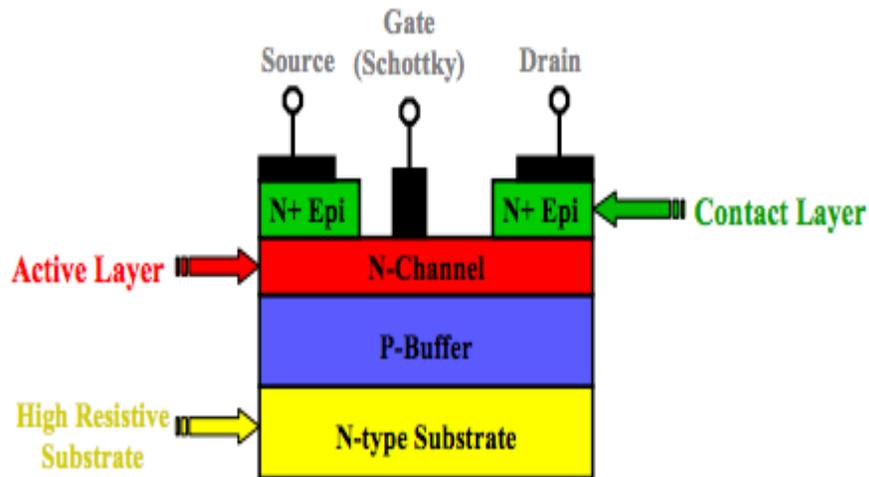


Figure 19.SiC MESFET Structure

### 3.2 SEMI-TRANSPARENT SiC SCHOTTKY DIODE:

“The semi-transparent SiC Schottky diode has "ultra-thin" (18 nm Ni/Ti) Schottky contact, a gold annular over layer and a gold corner-contact cushion. The new construction modeling shows the same crucial attributes as a more accepted 'thick contact' Schottky diode. Such diodes have a higher effectiveness for low energy X-rays than that of routine structures combined together with negligible self-fluorescence from the electrode materials”. It is shown in figure 20.

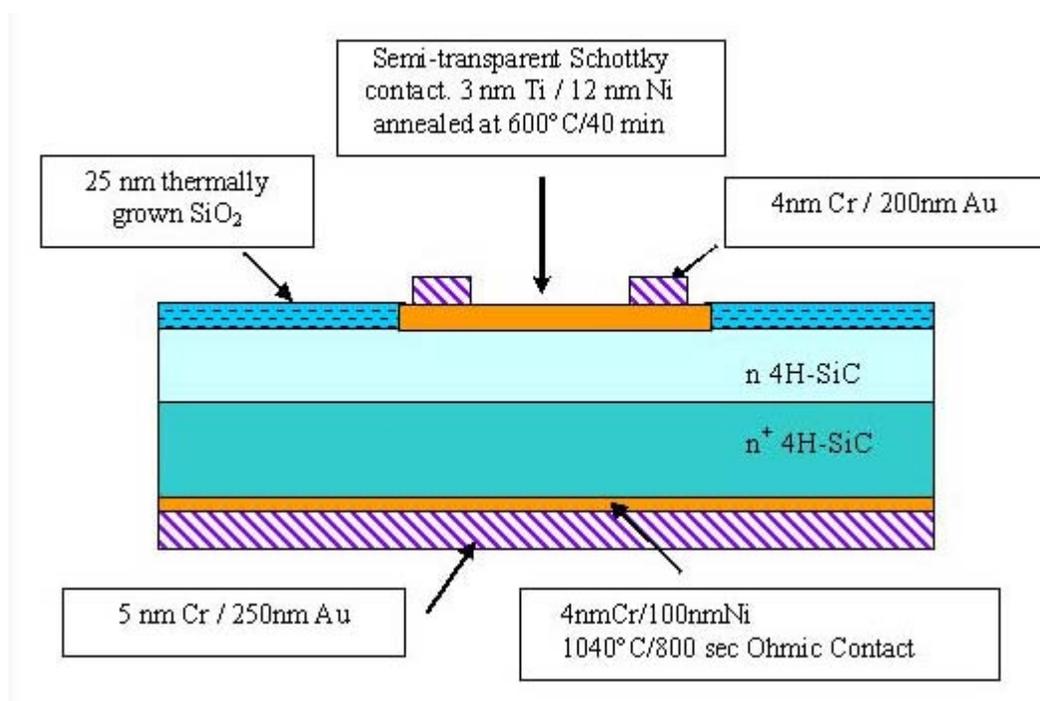


Figure 20 Section of 4H-SiC diode with semi transparent Schottky contact

### 3.3 DIODE FABRICATION:

#### 3.3.1 Grown Junction Diode:

“It is a type of diode formed during the crystal pulling process. P and N-type impurities are added one by one to the molten semiconductor material in the crucible, which then results to P-N junction. The bigger area device then might be curtailed into an expansive number of small area semiconductor diodes after cutting. The bigger area additionally presents more capacitive impacts, which are undesirable. Such diodes are utilized for low frequencies [30].”

#### 3.3.2 Alloy Typed or Fused Junction Diode:

“Placing a P-type impurity into the surface of an N-type crystal and heating the two until liquefaction occurs form an Alloy type or a Fused Junction diode. An alloy that will result on cooling will give a P-N junction at the boundary of the alloy substrate. Alloy type diodes have a high current rating and large PIV (Peak Inverse voltage) rating. The junction capacitance is also large, due to the large junction area. The figure 21. shows the alloy type or fused junction diode”.

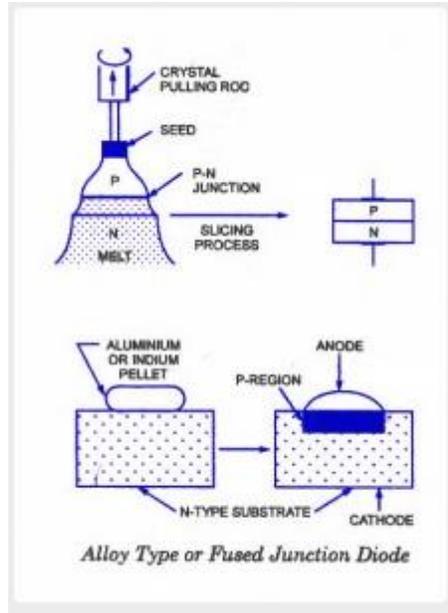


Figure 21. Alloy Type or Fused Junction Diode

### 3.3.3 Diffused Junction Diode:

“Diffusion is a process by which a heavy concentration of particles diffuses into a surrounding region of lower concentration. The main difference between the diffusion and alloy process is that the liquefaction is not reached in the diffusion process. In the diffusion process heat is applied only to increase the activity of elements involved. The process of solid diffusion starts with the formation of layer of an acceptor impurity on an N-type substrate and heating the two until the impurity diffuses into the substrate to form the P-type layer. A large p-N junction is divided into parts by cutting process. Metallic contacts are made for connecting anode and cathode leads [30]. In the process of gaseous diffusion instead of layer formation of an acceptor impurity; an N-type substrate is placed in a gaseous atmosphere of acceptor impurities and then heated. The impurity diffuses into the substrate to form P-type layer on the N-type substrate. Diffusion process requires more time than the alloy process but is relatively expensive, and can be very accurately controlled. The diffusion technique leads to the simultaneous fabrication of many hundreds of diodes on one small disc of semiconductor material and is most commonly used in the manufacture of semiconductor diodes.[30] Diffusion process is also used in the production of transistors and ICs(Integrated Circuits). Figure 22 shows Diffused Junction Diode”.

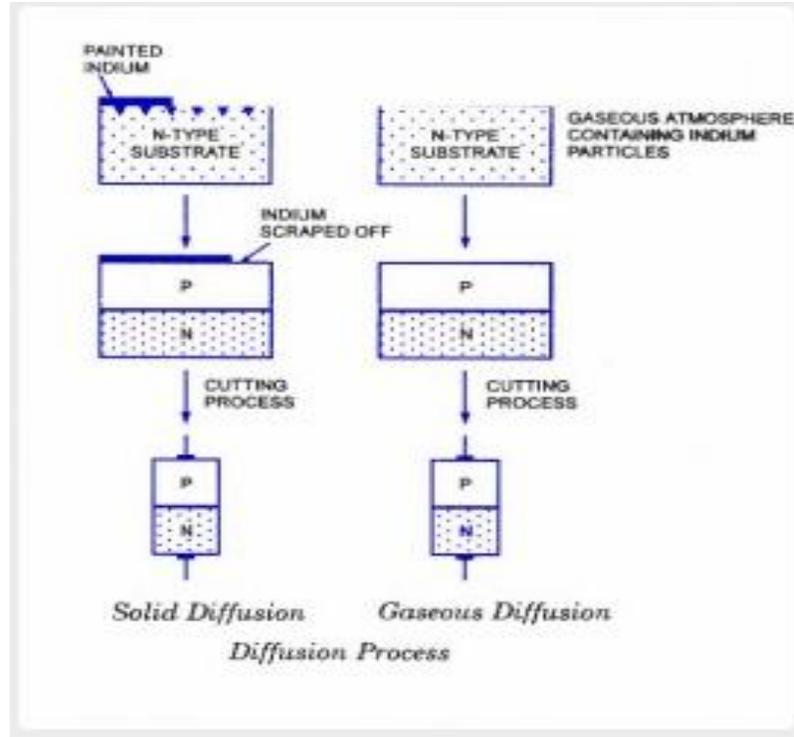


Figure 22. Diffusion Junction Diode

### 3.3.4 Epitaxial Growth or Planar Diffused Diode:

“The expression of epitaxial is determined from the Latin terms epi significance upon and axis importance arrangement. To develop an epitaxial developed diode, an exceptionally heavily doped layer of semiconductor material is developed on a vigorously doped substrate of the same material. This complete structure then shapes the N-region on which P-region is diffused. SiO<sub>2</sub> layer is thermally developed on the top surface, photo-etched and then aluminum contact is made to the P-region. A metallic layer at the bottom of the substrate structures the cathode to which lead is connected. Epitaxial Growth is as a method utilized in manufacture of IC chips” [31]. Figure 23 presents the epitaxial development of planar diffused diode.

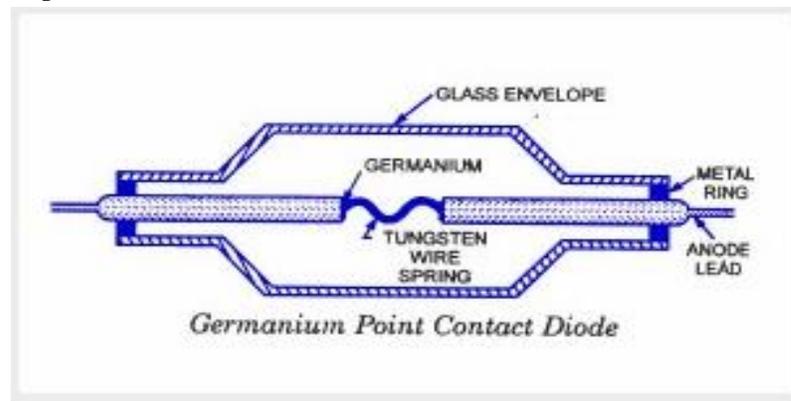


Figure 23 Point Contact Diode

## CHAPTER 4.

### 4.THEORY AND MODEL

A schematic cross-section of a silicon carbide MESFET is illustrated in Fig. 24.

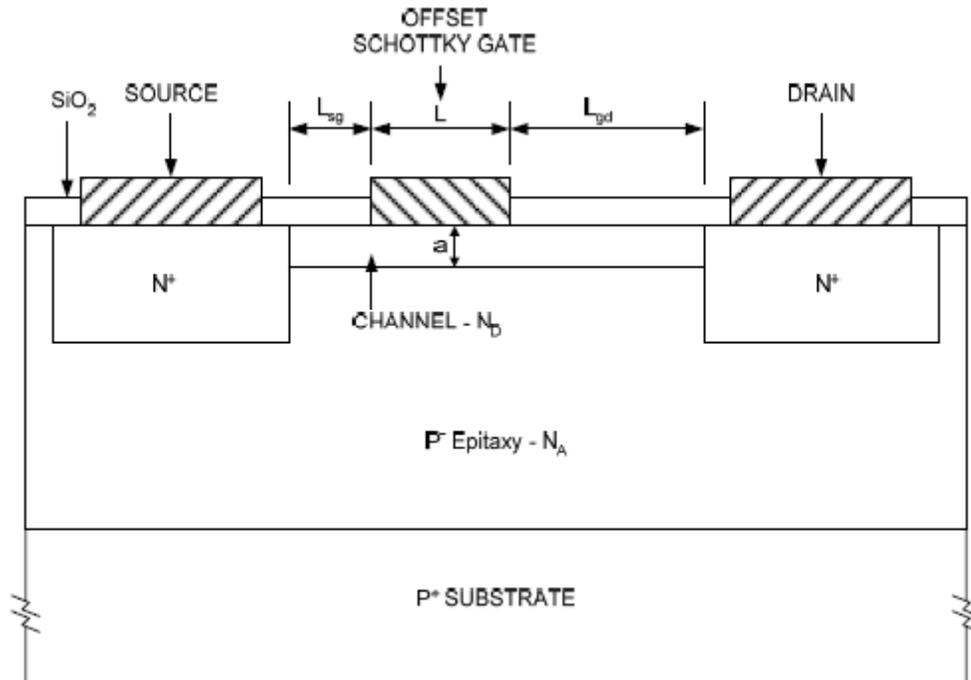


FIG 24.

The device structure parameters incorporate the length of gate  $L$ , width of gate  $W$  and depth of channel  $a$ , and so forth and a offset gate structure in the device has been acknowledged so as to enhance high power operation as depicted in the results and discussion area. A schematic cross-area of a Sic MESFET is shown in Fig. The apparatus structure parameters incorporate the length of gate  $L$ , width of gate  $W$  and depth of channel  $a$ , and so forth and a offset gate structure in the mechanism has-been recognized so as to enhance high power performance as portrayed in the results and discussions area. Acknowledging impurity diffusion because of annealing, the impurity dispersion can be represented by a symmetric Gaussian distribution as follows [32-37].

#### 4.1 I-V characteristics of a MESFET

The drain to source current in the region which is linear including the source which is parasitic and drain resistances can be found as given below:-

$$\int_0^L I_{ds} dx = qZ\mu \int_{I_{ds}R_s}^{V_{ds}-I_{ds}R_d} N_d (a - h) dV$$

$$I_{ds} = \frac{qZ\mu a N_d}{L} (V_{ds} - I_{ds}(R_s + R_d) - \frac{2}{3V_p^{3/2}} [(V_{bi} - V_{gs} + V_{ds} - I_{ds}R_d)^{3/2} - (V_{bi} - V_{gs} + I_{ds}R_d)^{3/2}]) \quad (4.1a)$$

Where:-

“ $I_{ds}$  = drain-source current”

“ $\mu$  =electron mobility”

“ $L$  = gate length”

“ $A$  = active channel thickness”

“ $V_p$ = pinch-off voltage”

“ $R_s$ = parasitic source”

“ $Z$  = gate width”

“ $R_d$  = drain resistances”

“ $V_{ds}$ = applied drain-source voltage”

## 4.2 C-V characteristic of SiC MESFET

It is exceptionally critical to have a correct model of capacitance for the re-enactment of high velocity analog and digital circuits. It plays noteworthy part on frequency exhibition and impedance, it is briefly shown below.

### 4.2.1 Gate Source Capacitance

The simplified charge disseminations are utilized to compute inner device capacitances. For microwave provisions the inner gate to source capacitance  $C_{gs}$  plays a critical effect on frequency exhibition and input impedance [38].

Charge disseminations under the gate are utilized to figure the internal device capacitance. Mathematically it might be written as:-

$$C_{gs} = \frac{\partial Q_1}{\partial V_s} + \frac{\partial Q_2}{\partial V_s} + \frac{\partial Q_3}{\partial V_s}$$

Where

$V_{gd}$ =voltage drop of gate to drain

$Q_1, Q_2, Q_3$ =Charge for internal distribution

$$Q_1 = \frac{ZqN_d a^2}{2} \left( \left( \frac{V_{bi} - V_g + V_s}{V_p} \right)^{1/2} + \left( \frac{V_{bi} - V_g + V_d}{V_p} \right)^{1/2} \right)$$

$$Q_2 = \frac{\text{III}qN_d a^2}{4} \left( \left( \frac{V_{bi} - V_g + V_s}{V_p} \right) \right)$$

$$Q_3 = \frac{\text{III}qN_d a^2}{4} \left( \left( \frac{V_{bi} - V_g + V_d}{V_p} \right) \right)$$

$V_s$ =Voltage of Source

$V_g$ =Voltage of Gate

$V_d$ = Voltage of Drain

Substituting the above equations in equation of  $C_{gs}$  we obtain gate to source capacitance:-

Equation 4.2.1a

$$C_{gs} = \frac{ZL}{2\sqrt{2}} \left( \frac{q\epsilon_s N_d}{V_{bi} - V_{gs}} \right)^{1/2} + \frac{\text{III}}{2} \epsilon_s Z$$

Where,

$C_{gs}$ =gate to source capacitance

$N_d$ =doping density  
 $V_{bi}$ =built in Voltage  
 $V_{gs}$ =gate to source potential  
 $q$ =charge of electron  
 $L$ =length of gate

#### 4.2.1 Gate drain Capacitance

We find internal gate to drain capacitance:-

Equation 4.2.1b

$$C_{gd} = \frac{ZL}{2\sqrt{2}} \left( \frac{q\epsilon_s N_d}{V_{bi} - V_{gd}} \right)^{1/2} + \frac{\epsilon_s Z}{2}$$

Where,

$C_{gd}$ =capacitance of gate to source  
 $N_d$ =doping density  
 $V_{bi}$ =built in voltage  
 $V_{gs}$ =gate to source potential  
 $q$ =charge of electron  
 $L$ =length of gate

#### 4.3 Transconductance of a MESFET

Transconductance is the main parameter for the determination of quality of device for microwave application. The transconductance is effected by the dimensions of device as well as material of the channel. The equation given below shows that the slope of  $I_{ds}$ - $V_{gs}$  gives us the transconductance ( $g_m$ ) keeping  $V_{ds}$  constant.[39]

Equation 4.3a

$$g'_m = \frac{g_m}{1 + g_m R_s}$$

Where

$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}}$$

## CHAPTER 5

### 5.Result and Discussion

This is simple physics based analytical model for non-self-aligned SiC MESFET. There has been continuous research going on to develop a better analytical model for evaluation of I-V characteristics, and it is observed that model for I-V characteristics doesnot match the non-saturation with the saturation region (linearity and non-linearity region). The present work shows huge impact of numerical iterative process to find the given characteristic in both the region.(linear and non-linear region).

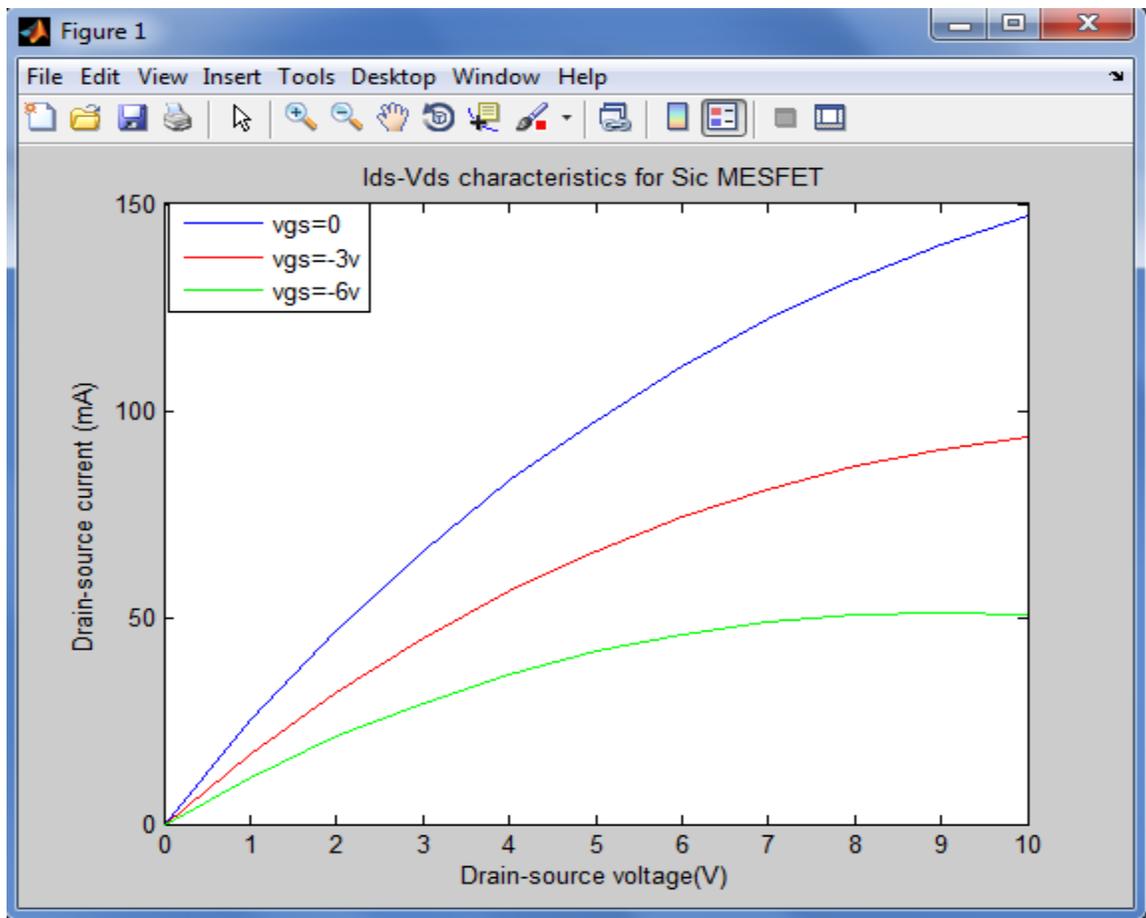


Figure 25 Drain to source current v/s drain to source voltage for varying gate to source potential.

The figure shows a plot of drain to source current v/s drain to source voltage for varying gate to source potential. It is plotted by varying gate to source potential ( $V_{gs}$ ) of 0V, -3V and -6V with doping concentration of channel( $N_d$ ) of  $2 \times 10^{17} \text{ cm}^{-3}$  and concentration of substrate( $N_a$ ) of  $5 \times 10^{17} \text{ cm}^{-3}$ . The current to voltage characteristics for gate to source voltage ( $V_{gs}$ ) of 0V, linearity properties are observed till 10V and non-linearity that is saturation region is observed beyond drain to source voltage ( $V_{ds}$ ) greater than 10V. The current of drain when gate to source potential ( $V_{gs}$ ) = -3V, linearity properties are observed till  $V_{ds}=8\text{V}$  and then the current starts saturating from  $V_{ds} = 8\text{V}$  and above  $V_{ds}=8\text{V}$ . When  $V_{gs} = -6\text{V}$ , linearity of current of drain shows till  $v_{ds} = 7\text{V}$  and non-linearity properties is found from  $V_{ds} = 7\text{V}$  and after  $V_{ds}=7\text{V}$ . The linearity properties and non-linearity properties of current to voltage characteristics till upto the breakdown point can be observed using the iterative method. This plot has been generated by using the Equation 4.1a

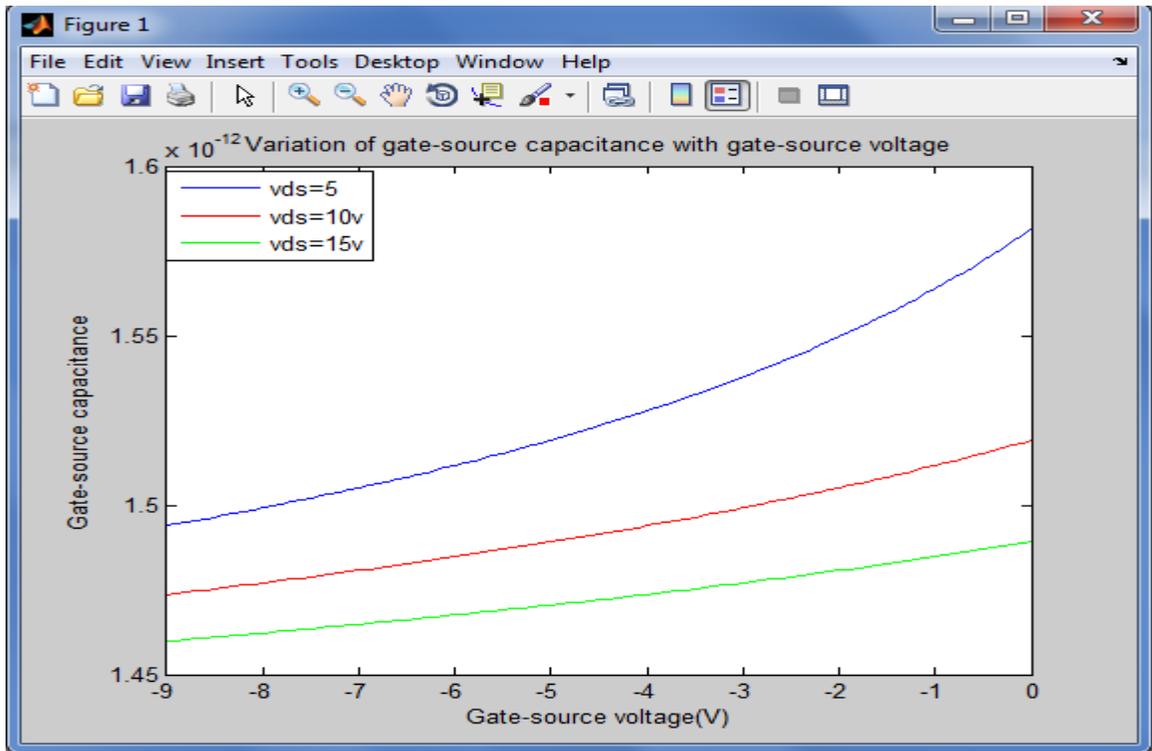


Figure 26 Gate to source capacitance ( $C_{gs}$ ) v/s gate to source potential ( $V_{gs}$ ) for varying drain to source potential ( $V_{ds}$ )

The plot of gate to source capacitance  $C_{gs}$  v/s gate to source potential  $V_{gs}$  for different drain to source potential  $V_{ds}$  is shown in figure 26. With the increment of gate-source voltage from -9V to 0V is gate-source capacitance increases exponentially. Gate capacitance is higher for the drain to source potential  $V_{ds} = 10\text{V}$  and the nature of curves

of other  $V_{ds} = 12V$  and  $15V$  are similar to the  $C_{gs}$  curve for  $V_{ds} = 10V$ . Charge in the gate depletion layer increases that increases the gate to source capacitance as the gate to source potential becomes more positive. The plot is developed by using the equation 4.2.1a

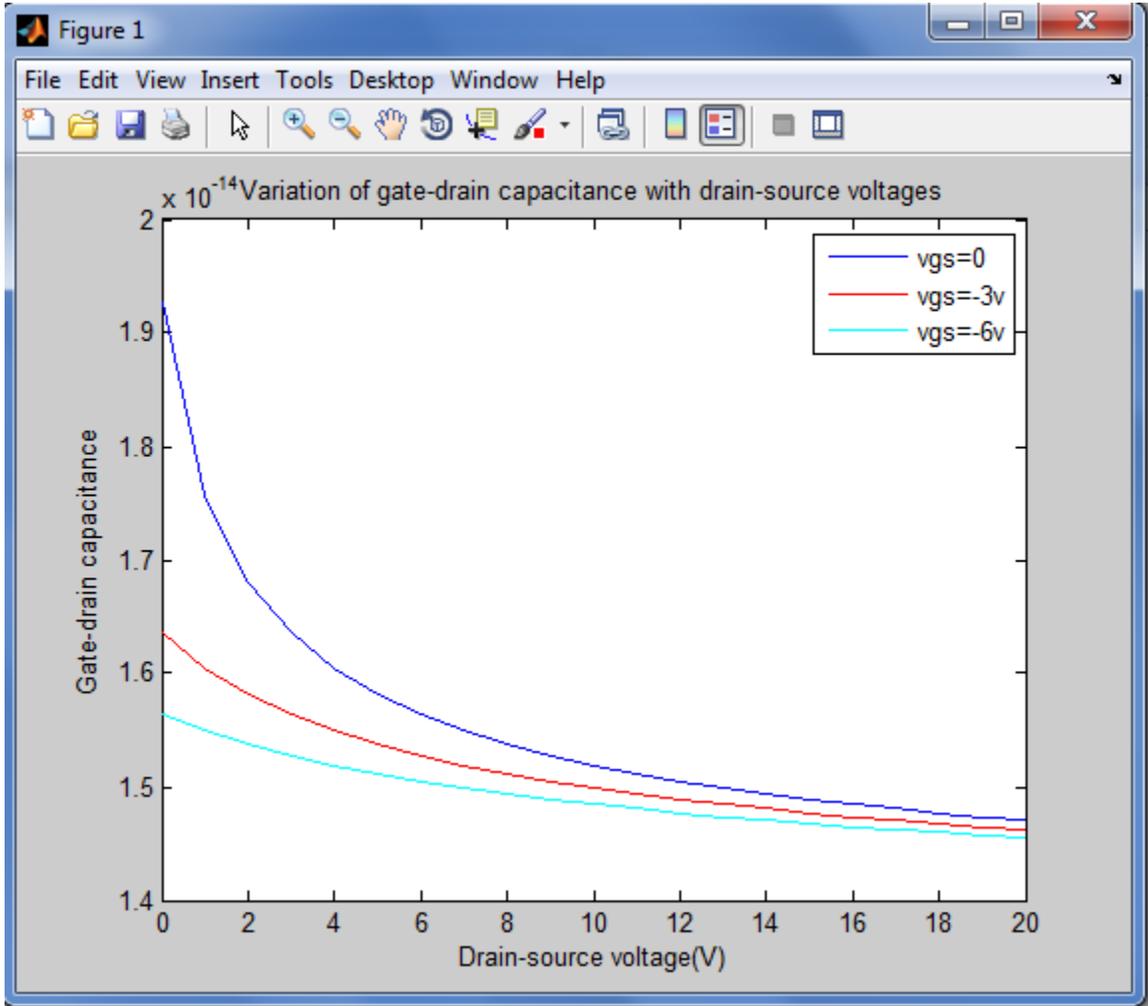


Figure 27 gate-drain capacitance  $C_{gd}$  versus drain-source voltage  $V_{ds}$  for different gate-source voltage  $V_{gs}$

Figure 27 shows gate-drain capacitance  $C_{gd}$  versus drain-source voltage  $V_{ds}$ . It is for different gate-source voltage  $V_{gs}$  of  $0V$ ,  $V_{gs}$  of  $-3V$  and  $V_{gs}$  of  $-6V$ . As soon as drain to source voltage increases then gate to drain capacitance increases exponentially. The maximum gate to drain capacitance is obtained for  $V_{gs} = 0V$  due to large charge stored in the depletion region of gate. At high drain voltage in the range of  $V_{ds} = 16$  to  $20V$ , the gate

drain capacitance for  $V_{gs} = 0V$ ,  $V_{gs}=-3V$  and  $V_{gs}=-6V$  becomes saturated .This plot has been drawn using the Equation 4.2.1b .

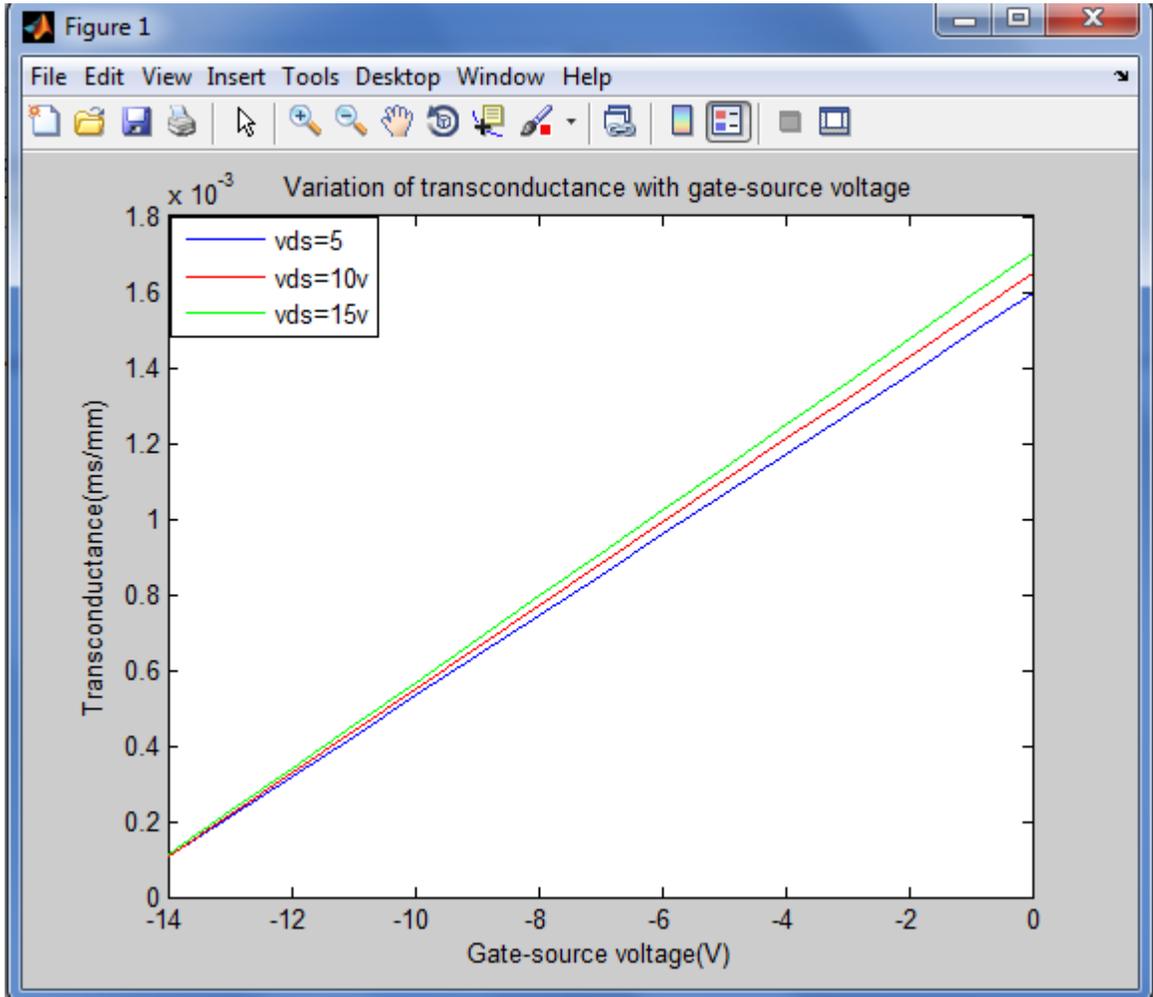


Figure 28 Transconductance ( $g_m$ ) versus gate-source voltage ( $V_{gs}$ ) for different drain-source voltage  $V_{ds}$

As shown in the above figure Transconductance varies linearly with Gate source voltage. As Gate source voltage goes from -14 to 0 V, Transconductance changes from 0 to  $1.8 \times 10^{-3}$  respectively. From the crossing point of gate voltage, the built in voltage is discovered to be roughly in the range of -14v to 14.5v. The plot has shaped by utilizing the Equation 4.3a

## **CHAPTER 6**

### **CONCLUSION**

Analytical modeling with numerical calculations and software simulations have been performed for evaluation of the threshold voltage, drain-source current, breakdown characteristics, intrinsic parameters, cut-off frequency and other related parameters for 4H-SiC MESFET.

The results show the potential application of the device for high power and high frequency amplification for the aerospace and defense telemetry and communication applications.

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