A THREE REGION ANALYTICAL MODEL FOR SHORT CHANNEL SILICON CARBIDE (SiC) MESFET's

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By

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# TABLE OF CONTENTS

**SIGNATURE PAGE** ii  
**ACKNOWLEDGEMENT** iii  
**LIST OF FIGURES** vi  
**LIST OF TABLES** viii  
**ABSTRACT** ix  
**CHAPTER 1: Introduction** 1  
**CHAPTER 2: Silicon Carbide (SiC)** 7  
  2.1 The new manufacturing technologies in Silicon Carbide 7  
  2.1.1 Acheson process 7  
  2.1.2 Sintered Silicon Carbide 7  
  2.1.3 Carbon felt-Silicon Carbide 9  
  2.1.4 Chemical Vapor Deposited SiC 10  
  2.2 Silicon Carbide crystalline structure 10  
  2.2.1 Basic Structure 10  
  2.2.2 Polytypism 11  
  2.2.3 Impurities in Different Polytypes 12  
  2.3 Properties of Silicon Carbide 15  
  2.3.1 Mechanical properties 15  
  2.3.2 Thermal Properties 19  
  2.3.3 Optical Properties 23  
**CHAPTER – 3: MESFET’s Technology** 25  
  3.1 MESFET 25  
  3.2 MESFET Types 25  
  3.3 MESFET Structure and Characteristics 26  
  3.4 SIC MESFET Structure and Characteristics 27
3.5 Fabrication in MESFET 28
3.6 Advantages and Applications of MESFET’s 31

CHAPTER- 4: Model and Numerical Calculations 32

4.1 Silicon Carbide MESFET 32
4.2 I-V Characteristics 33
4.3 Transconductance in Silicon Carbide MESFET 36

CHAPTER 5: Result & Discussion 37

CHAPTER 6: Conclusion 41

REFERENCES 42

Appendix A 45
Appendix B 46
LIST OF FIGURES

Figure 1: Longitudinal cross section of SiC 3
Figure 2: Radial cross section of SiC 4
Figure 3: A flowchart of the Sintered Silicon Carbide (SSiC) manufacturing process 8
Figure 4: A flowchart of the Carbon felt-Silicon Carbide manufacturing process 9
Figure 5: The characterization of tetrahedron building blocks for all the SiC crystals 11
Figure 6: The illustration the three closed packed planes of spheres 11
Figure 7: The three different type of common polytypes in SiC viewed in [1120] plane 13
Figure 8: The above Figure represents the near-band-edge phenomenon of photoluminescence spectrum that has the atoms of 4H-SiC 14
Figure 9: Weibull diagram for Boostec SSiC 17
Figure 10: Weibull diagram for POCO Carbon felt SiC under different conditions 18
Figure 11: Coefficient of thermal expansion with respect to temperature 19
Figure 12: Thermal expansion from 293 K with respect to temperature 19
Figure 13: The plot shows temperature and thermal conductivity characteristics 20
Figure 14: The plot shows temperature and Specific heat characteristics 20
Figure 15: Volumetric thermal stability of Sintered SiC with respect to temperature 21
Figure 16: Reflectivity of Silicon Carbide in the visible spectrum 23
Figure 17: Absorption coefficient versus wavelength 23
Figure 18: Transmittance versus wavelength 24
Figure 19: Basic structure of MESFET 26
Figure 20: I-V characteristics of MESFET 27
Figure 21: Basic structure of SiC MESFET’s 27
Figure 22: Characteristics of SiC MESFET's

Figure 22(a): I-V Characteristics of the SiC MESFET's  
Figure 22(b): Transfer Characteristics of SiC MESFET's

Figure 23: MESFET fabrication process

Figure 24: The cross-sectional view of silicon carbide MESFET showing the three regions in high drain voltage

Figure 25: $V_{DS}$ versus $I_{DS}$ characteristics where $V_{GS}$ is kept constant

Figure 26: $V_{DS}$ versus $I_{DS}$ characteristics where $V_{P}$ is kept constant

Figure 27: Transconductance ($g_m$) versus gate-source voltage ($V_{GS}$) where $N_d$ kept constant
LIST OF TABLES

Table 1: Shows the different Mechanical properties of Silicon carbide and the other materials which are related to it at room temperature 16

Table 2: Scaling stress and Weibull modulus 18

Table 3: Thermal expansion of Sintered Silicon Carbide, Carbon felt Silicon Carbide, TiAl6V4 and fused silica for a temperature change of 293 K to 100 K and the coefficient of thermal expansion at 100 K 22
ABSTRACT

A THREE REGION ANALYTICAL MODEL FOR SHORT CHANNEL SILICON CARBIDE (SiC) MESFET's

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Master of Science in Electrical Engineering

This project presents an improved analytical model of the three regions in a SiC metal semiconductor field effect transistor (MESFET). The analytical model mainly focuses on two regions in the active channel that are between gate-source and drain-source. The third region gate-drain (which is ungated) is ignored in this analytical model due to the very large potential drop at high drain voltages in a short channel device. In order to improve the accuracy in this model, the parasitic resistance and incomplete ionization of dopants have been incorporated. Considering these effects in the analytical model, a simulation of the current and voltage characteristics and transfer characteristics of the Silicon Carbide MESFET has been developed and discussed in detailed in this thesis.
Silicon carbide is one type of semiconductor which is made up of equal parts of silicon and carbon. Its chemical formula can be represented as SiC. In SiC both the silicon and carbon are elements in the IV column in the Table of the Elements. These types of semiconductors only prefer covalent bonding. Also, every carbon atom in silicon carbide is surrounded by four silicon atoms and each silicon atom in the silicon carbide is surrounded by four carbon atoms. As a result this will lead to a high ordered configuration of one single crystal. If the crystal is polarized, we can easily identify a silicon face as well as carbon face, which provides each and every atom with a free bond. In contrast, gallium arsenide has only a one crystal structure, while silicon carbide has a multi-crystal structure. Because there is exactly only one silicon atom for each and every carbon atom, let’s think of this atom as a unit symbolized by a ball. The most efficient way to combine all the balls is in a hexagonal fashion, which is also known as the crystallographic form called as Hexagonal Close Packing. The layer of balls which are present in a double layer are from silicon and carbon atoms. The next layer is always to be displaced according to the structure of the covalent bonding scheme.

Silicon carbide is also referred as Carborundum. SiC can occur in nature in the form of minerals called Moissanite under extremely rare conditions. Silicon carbide powder has been generated in mass from 1893 for use in abrasive materials. For example, it is incorporated in car clutches, ceramic plates, car brakes and one of its most important uses is in bulletproof vests. Silicon carbide is mainly applicable in Light Emitting diodes (LEDs) in electronic terms which started in 1907. Now-a-days Silicon Carbide plays a vital role in high voltage and high temperature semiconductors in electronics. High quantities of single crystals can only be formed by using the method called Lely for silicon carbide. It can also be used to cut into gems, which is called as synthetic Moissanite. A form of SiC with a very high surface area can be produced with this method from SiO2.

Moissanite can occur naturally in very small quantities and are divided into certain types of meteorite and corundum. In the whole world, all the silicon carbide and jewels including specific jewels such as Moissanite are synthetic. The first Moissanite jewel was introduced in 1893 in with fewer components by Dr. Ferdinand Henri Moissan, at the Canyon Diablo meteorite in Arizona State. In 1905 this material was named and came into existence [1].

In space, silicon carbide is a remarkably rare occurrence. At present, it has become a common material emitted by carbon-rich stars in the form of stardust [2]. The examples of the stardust can only found in the condition of unaltered meteorites. Which is related to the ratios of silicon as well as carbon, which shows the starting point from the outside; Out of 100%, SiC
grains originate around 99% and the else is originated by the carbon rich giant branch stars [3].

The silicon carbide is commonly found in this starts as a infrared spectra which are deducted [4].

SiC has the non-oxidizing properties of ceramic which is important in semiconductor, in that it has very high diverse electric applications. In addition to this, an industrial application requires high melting point, thermal stability, chemical stability, high resistance, high oxidation and high erosion resistance and many more. These kinds of applications make silicon carbide a perfect semiconductor of high temperature and power electronic devices as well as cutting applications and many abrasion resistant applications. In the year 1892, there were several inventions related to Silicon Carbide synthesis.

The introduction provides a brief summary of different Silicon Carbide structures and about different polytypes which are encountered. We have to mainly study up on the different fabrication steps in silicon carbide that starts from an Acheson process and leads to a high extent in SiC. These types of processes are mainly dependent on the carbothermal in the reduction method only after the operation of silicon carbide powder. In this process, it mainly undergoes a number of steps that has great demand in the energy which provides a poor quality material. The alternative to the previous method has been reported for silicon carbide production. The most common method of silicon carbide depositions are:

- Chemical Vapor Deposition (CVD),
- Physical Vapor Deposition (PVD),
- Liquid Phase Sintering (LPS) and
- Mechanical Allying (MA), sol-gel will be detailed. Due to electrical and structural properties of silicon carbide, fabrication can also be discussed as the synthesis methods of functioning.

Currently, there are more than 200 silicon carbide polytypes which have been found up to date. These prototypes are proved by many authors and are dependent upon the type of orientation known as seed orientation. In the year 1992 and 1993, they had attributed the phenomenon upon different types of energies such as surfaces of carbon and silicon faces that influence different polytypes nuclei formations. The cubic zinc blende can also be written as 3C-Silicon Carbide or β-Silicon Carbide. The polytypes which are hexagonal consist of rhombohedra, nH-SiC polytypes nR-SiC, also called α-SiC, which consists of a bilayer of Carbon; Silicon stack layers of the primitive cell in the year 2008.

In the year 1891, the scientist Acheson discovered a large scale method for the preparation of silicon carbide [5]. In this manufacturing process we can discuss many things in later chapters. Acheson believed that these materials were a combination of both compounds of Corundum (Al2O3) and Carbon. At present, silicon carbide is produced at an excess rate of 900,000 tons in one year. Among these productions, only Abrasive industry has the largest amount of silicon carbide production. Due to its great hardness, it is very much suitable for these types of industries such as the abrasive industry and this is also one of its applications. It is often
used with abrasive materials and tools. Another large production of silicon carbide and its application was made by the carburizing of silicon agents of both the steel and iron metallurgy. As a result, the development of bonded silicon carbide in the molded form has been started from the mid 1960’s onwards. Nowadays, this type of hot-process industry only makes use of the silicon carbide for refractories such as setter tiles, fire bricks, heating elements and also the tubes.

Currently, silicon carbide is used more than its usage before and it is also used in mechanical engineering for the structural components. This material had already proven successful under the extreme conditions involving corrosion, abrasion and high temperatures. Examples of these materials are sealed rings in cars for water pumping, brake discs in cars such as sports cars and F-1 cars, etc. Compared to high temperature application, the silicon carbide has interesting structural parts applications which are growing extremely fast in different environments or applications such as semiconductor and space industry. These types of applications mainly require extremely exact shape. The main application of silicon carbide in the industry such as space is to make use of the mirrors [6].

The production of Silicon Carbide by the Acheson process can be explained by using the pictorial representation:

This process mainly consists of two cross section and they are:

1. Longitudinal cross-section
2. Radial cross-section

Figure 1: Longitudinal cross section of SiC
In longitudinal cross section, the production of silicon carbide is shown in Figure 1. Here the silicon carbide cylinder is in the center part of the cross section and radiated by the reactive mixture which consists of carbon and boron and centered in the core of the specified resistance with the overall length specified as 25m. The total cross section is on the canopy. This resistance core is connected to the current conductors as electrodes using a porous bed at the center. These current electrodes have been placed on the floor to avoid contact [7].

![Diagram of cross section](image)

Figure 2 Radial cross section of SiC

In the radial cross section shown in Figure 2, the silicon carbide cylinder is connected in a cylindrical fashion and consists of a reaction mixture with the resistance core as the center. Compared to the longitudinal cross section, the radial cross section has a smaller diameter of 4m. In this cross section, the electrodes should not be connected to the current but to the gas collection duct in the ground which is surrounded by the porous bed. Similar to the longitudinal cross section, the radial cross section is also covered by the canopy.

The sintered silicon carbide materials use the α-SiC crystals from the above Acheson process as the base material. There are many different types of forms of SiC. For example hot or isostatically pressed SiC (HIPSiC or HPSiC), liquid-phase sintered SiC (LPSiC), and the solid-state sintered SiC (SSiC) [7].

Beside silicon carbide elements, we are also using gallium nitride elements in our study. Let us see some basic information regarding the gallium nitride element in this study.
Silicon carbide and gallium nitride, being wide band-gap semiconductors, can be suitable for microwave power generation at X-bands and ultra high frequency bands. The advantages of SiC and GaAs compare to the wide band materials are having high saturation velocity, breakdown field and high thermal conductivity. The specifications of SiC MESFET are 250μm peripheral devices, having a record power density of 5.6 W/mm with a frequency of 3GHz. Compared to SiC, GaN having high electron mobility, can offer very high performance in the high electron mobility transistor (HEMT) family of devices due to high carrier sheet density with a saturation velocity of 2V and a record power density of 10W/mm.

Gallium Nitride is an III-V in binary state, and is used as a band gap semiconductor which are have been very popular in LEDs from 1990s. Due to the presence of an about 3.4 eV band gap, GaN has properties that are very useful in other applications in addition to optoelectronics, such as very high- frequency and very high-power devices. As a result Gallium Nitride provides very high breakdown voltages and also provides high temperature tolerance and high power added efficiency in the applications of RF and microwave power as well as reliable and efficient switching devices used in high voltage power grid applications. The solutions that use Gallium Nitride are mainly based upon the RF transistors and are also replaced by the magnetrons that are mainly used in microwave ovens. Gallium Nitride transistor models are evolved from the Gallium Arsenide transistor models. While comparing the advantages, Gallium Nitride offers:

- A very high operating voltage i.e., over 100 V breakdown
- A very high operating temperature which is over 150°C temperature in channel region
- A very high power density which is ranging from 5 to 30 W/mm
- Crack-resistant and durable material

The basic similarity for the Gallium Nitride devices and Silicon Carbide devices is that these GaN (Gallium Nitride) are basically grown on the SiC (silicon carbide) substrates, but the important thing is to achieve the low cost of Gallium Nitride devices. These Gallium Nitrides provide a wide band gap that allow high breakdown voltages and also operate usually in extreme high temperatures. This thermal conductivity in SiC is very high and as a result provides a better substrate than the silicon for the power amplifier applications that requires a very good heat sinking property.

Gallium Nitride is a hard material and is used in fabricating pure crystalline wafers in bulk and has proven to be a very good and complicated applicable material. Gallium Nitrides are very limited in use to small area devices mainly in LED’s and are specialize in the military and laser applications which easily absorb the high costs of the small area wafer for processing. An advanced category in the vapor phase epitaxial growth and chemical vapor deposition is done during 1990’s deposited on silicon carbide wafers and silicon wafers. This technique can provide the accessibility of the large-scale fabrication. Gallium Nitride devices can also be processed on
the Silicon or Silicon Carbide wafer substrates significantly improves the thermal performance compared to the devices such as Gallium Arsenide wafers. Gallium Nitride has wider band gap of 3.4 eV, Silicon has 1.2 eV and Gallium Arsenide has 1.4 eV. This band gap allows the Gallium Nitride devices to operate at very high temperatures without degrading and which are designed in such a way that, they may operate at higher operating voltages.

The above properties of Gallium Nitride easily results in a device providing the highest power density. While maintaining the wide bandwidths at a certain frequency which is ranging up to 4 GHz rather than the other competing technologies provides high ionization resistance i.e., radiation hardness, surge voltage tolerance and increased ESD will make the Gallium Nitride based devices an excellent choice for high power military radio frequency applications. Recently, Gallium Nitride radio frequency devices have been started to challenge the Silicon LDMOS at a frequency of 2 GHz. WI MAX power amplifiers are used at the base station market, while Gallium Arsenide MESFET’s devices are optimized for operating at low voltages. The unique property of Gallium Nitride devices initially can easily be targeted only for the military applications which are operating at 50 volts. The wafer fabrication process can be optimized for these types of devices operating at 24 volts is similar to RF amplifier working voltages.

The implementation of thermal conductivity in Gallium Nitride is 2 times higher than Gallium Arsenide i.e., \( \text{GaN} = 2 \times \text{GaAs} \). The fabrication on the Silicon Carbide wafer substrates at \( T_c = 4.9 \text{ W/cm}^2\text{K} \) allows GaN devices to operate and to easily maintain the safe junction temperatures. Motorola’s hybrid circuit technology, which is patented in the conjunction to the robustness of Gallium Nitride semiconductor properties.

MESFET devices are totally different from the insulated gate devices such as metal oxide semiconductor field effect transistors (MOSFETs). The MESFET structure does not have the gate insulator, rather the gate metal forms a schottky junction with the channel region. Therefore, the MESFET must be operated within certain limits such that the gate is not forward biased. The MESFET controls the current through the channel by modulating the depletion region under gate contact, acting similar to the Junction Field Effect Transistor (JFET). Some advantages of the MESFET operation is that the carriers in the channel are majority carriers (rather than minority carriers as in the MOSFET), and the schottky junction is having significantly less capacitance.
2.1 THE NEW MANUFACTURING TECHNOLOGIES IN SILICON CARBIDE

There are a large number of manufacturing technologies for Silicon Carbide. It is not only the intention of this study to discuss all this manufacturing techniques in detail, because some of the techniques in manufacturing are not interested in the application of the Basic angle monitoring system (BAM) in a given space application. Here the small selection of the manufacturing techniques are discussed. The earliest SiC sintering process was the Acheson process, which led to a variety of developments in processes for producing sintered Silicon Carbide. The production of the sintered SiC products is explained in the following steps. Carbon base production of silicon carbide can be technically expressed as Carbon SiC method and it is the next manufacturing technique discussed in this study.

2.1.1 Acheson process

This is the first manufacturing technique for the production of A-SiC i.e., Acheson Silicon Carbide with a hexagonal crystal structure, which can be executed by Acheson process. In this type of process, some part of the mixture is made with high purity quartz called silicon dioxide (SiO₂) and also with the petroleum coke (C). Then this mixture is kept in the rectangular furnaces stacks with a dimensions of 25m long, 4m height and 4m wide. At the two ends of the furnace a water-cooled graphite electrode rod is present in order to cool the system. This graphite rod is connected to electrodes in the underneath. In this system we have to apply a current of 25×10³ Amps to the electrodes and then heating the furnace at a temperature of 2500 °C. This will result in the Silicon Carbide to crystallize outwards.

In conclusion, a high-purity of large A-Silicon Carbide crystals which are in hexagonal crystal structure have been created at the center of the mixture and in-turn form a fine crystal of Silicon Carbide, which are in cubic crystal structure. Here the current is switched off after 16 hours. Then by cooling down this mixture is removed in a layer by layer fashion.

2.1.2 Sintered Silicon Carbide

Sintered SiC is another type of manufacturing technique that make use of A-SiC crystals formed from the Acheson process as the base material. There are many different types of sintered SiC (SSiC). Let us see each of them:
1. Liquid-phase sintered Silicon Carbide (LPSiC)
2. Hot pressed Silicon Carbide (HPSiC or HIPSiC)
3. Solid-state sintered Silicon Carbide (SSiC).

The Sintered Silicon Carbide technically (called SSiC) can be processed by making use of manufacturer of Silicon Carbide mirrors and other structural parts of the space applications called as Boostec [8]. In detail we can say that the Boostec SSiC production process has been divided into following steps which is shown in Figure 3. The first step A-SiC powder produced with the existing Acheson process and get mixed with organic binders and also with the sintering aids which includes boron and carbon.

The resultant mixed powder is then compacted with the under cold isotactic pressing. This can be done by keeping the powder mixture in a large rubber bag. Then the bag is sealed and also submerged in a vessel which is filled with a fluid. This fluid with the existing powder bag is then applied with a pressure of \(200 \times 10^6\) Pa. After applying the pressure, this results into a ‘green’ Silicon Carbide block of compacted powder, which has chalk-like behavior. The behavior of the ‘green’ SiC can only be verified by testing the strength of small dummies of the resultant powder.

![Figure 3: A Figure of the Sintered Silicon Carbide i.e., SSiC construction process](image)

The ‘green’ SiC block is then machined to resultant desired shape i.e. green shape. The green shape is then applied to a pressure of less sintered. This less sintering is only performed at the temperature of 2100°C in non-oxidizing nature in a graphite electrical furnace. This sintering process will take in the order of days to weeks to perform, depending upon the thickness of a product. If the thickness is too large, the cooling down trajectory will take a long time to keep the temperature difference between the core and edge, as a result no micro-cracks occur and this is
due to thermal stresses. During this manufacturing, the products can shrink a maximum of approximately 17%.

2.1.3 Carbon felt-Silicon Carbide

Carbon felt-Silicon Carbide can be technically expressed as CSiC and is also called as reaction-bonded Silicon Carbide (RB SiC) [9]. Generally in this type of process a gaseous Silicon dioxide invades the carbon to pre-form. Sometimes this obtained pre-form also contains Silicon Carbide fibers and carbon-containing binder. Then the carbon reacts with this silicon to form the Silicon Carbide. If there is any excess portion of silicon, then the existing pores are filled up with the silicon. There is an American company named Poco Graphite which makes Carbon felt Silicon Carbide products for military and space applications [10]. The working of graphite rod is shown in following steps.

• The graphite felt block which is very fine and open porous structure has been produced.
• The graphite felt is also purified;
• The graphite felt is then machined to a desired shape i.e., green shape
• Then the carbon is infiltrated with the existing silicon and converted into Silicon Carbide.

The manufacturing process of CSiC is shown in Figure 4. This type of graphite conversion is only performed by the carbo-thermal reduction of silica atoms. In this process quartz i.e., silicon dioxide and solid carbon reacts at a temperature which is equal to 1600°C creating a gaseous silicon oxide. Therefore, the obtained Silicon oxide reacts with the carbon to form Silicon Carbon. Then the maximum infiltration depth can only be achieved with the process, which is around 6 mm. This infiltration process takes few days.

Figure 4: A flowchart of the Carbon felt-Silicon Carbide manufacturing process
This type of conversion can only be achieved by the infiltration of silicon which is in liquid state with the graphite felt using of capillary forces. This conversion technique makes use of Xycarb Ceramics. The infiltration depth of silicon semiconductor uses the capillary forces which is not limited for the graphite blocks and it is as large as 1 m³. Carbon-felt Silicon Carbide materials does not show any type of shrinkage. Generally they can only exhibit a small shape change with a maximum of 1 %.

2.1.4 Chemical Vapor Deposited SiC

Chemical Vapor Deposited can be technically expressed as CVD Silicon Carbide and it is obtained by the chemical vapor reaction of the volatile carbon and silicon atoms. In CVD SiC, the compounds are in the presence of hydrogen at a temperature range from 1000 °C to 1800 °C. CVD Silicon Carbide provides high purity at a range of 99.999 %. It consists of a b-SiC structure and it has very fine grains [10]. For the BAM system application, the CVD SiC manufacturing process can be used for the coating of Sintered Silicon Carbide or Carbon felt Silicon Carbide substrate for the mirror applications, because of high reflectance in this visible spectrum. As a result this can be polished up to 0.3 nm roughness. Physical Vapor Infiltrated (PVI) Silicon Carbide and the Chemical Vapored Deposition Silicon Carbide are also used in this coating.

2.2 SILICON CARBIDE CRYSTALLINE STRUCTURE

2.2.1 Basic Structure

The basic building block of the silicon carbide crystal atom is tetrahedron of four carbon atoms in which the silicon atom is at the center as shown in figure 5. In this building, they also exists a second type rotated structure of 180° angle variation with respect to the first block. The measurable distance between the silicon and carbon atom is 1.89Å and the distance between the each carbon atom is 3.08Å [11]. Silicon Carbide crystals are only constructed with these measurements.
Figure 5: The Figure shows the characterization of tetrahedron building blocks for all the Silicon Carbide crystals.

There are four carbon atoms which are covalently bonded with a single Si atom at the center as shown. There are two type of representation. One is rotated 180° angle around the c-axis with respect to the other and vice-versa, as shown in above Figure 5.

2.2.2 Polytypism

Silicon carbide semiconductor exhibits two-dimensional polymorphism called polytypism. All polytypes are present in this block have a hexagonal frame of Silicon Carbide bilayers. This hexagonal frames can be seen as a sheet of spheres or circles, which is of same radius and radii respectively which is illustrated in Figure 6.

Figure 6: Illustration of three closed packed planes of spheres.
The first layer is named “A” atom layer, followed by “B” atom in a certain position, with a next layer of atoms on “C” positions on the top of these layers. The resulting structure shown Figure 6 is 3Carbon Silicon Carbide.

The sheet follow the same measurements for all lattice planes. However, the position which is related to the plane directly shifted to fit in the “valleys” in a close-packed arrangement of the adjacent sheets. As a result there are two non-equivalent positions for each adjacent sheets. As a reference to the following possible positions of A, B, and C, we can now begin with the constructing polytypes shapes by arranging these sheets in a repetitive order within a specific type. Thus, there is only one cubic polytypes in Silicon Carbide called 3C-SiC, which has the sequence ABCABC… that has to be stacked. The simplest hexagonal structure, which can be easily build by using of 2H, having the sequence of ABAB…. The two important polytypes, 6H-SiC and 4H-SiC, have their own stacking sequences ABCACBABCACB… and ABCBABC…, respectively.

The sequence that is represented in the notation will result in crystal structure and that determines the possible number of layers before the resultant sequence repeats on itself. Some of the crystal shaped structures are listed below:

- C = cubic
- H = hexagonal and
- R = rhombohedral.

All the present polytypes of Silicon Carbide are made up of equal proportions of carbon and silicon atoms. Due to the effect of the stacking sequence in between this plane, the optical and electronic properties differ. The band gap is at an instance of 2.39 eV for 3-Carbon Silicon Carbide, 3.023 eV for 6Hydrogen- Silicon Carbide and 3.265 eV for 4Hydrogen Silicon Carbide [12]. This type of unit cell is different for different polytypes and will be naturally varied from origin depending upon the number of atoms per unit cell. This might affect the number of electronic bands and the number of the phonon branches for all given polytypes.

2.2.3 Impurities in Different Polytypes

Now, let us see some different types of impurity polytypes, which is a very beautiful feature in the behavior of impurity atoms. As shown in Figure 7, the impurity atoms may resemble the sites that are not equal to the hexagonal polytypes, i.e., 6H-Silicon Carbide and 4H-Silicon Carbide. The difference mainly occurs in the second nearest neighboring atoms. Here the nitrogen atom can be substituted with a carbon atom within the lattice point, which can be either occupying a “h” site or “k” site in the 4H-Silicon Carbide. The k site represents a lattice site
which only displays the cubic symmetry and the h site represents the hexagonal symmetry. Here we can also see the immediate vicinity for the nitrogen atom, whereas on the other site will be having the same atoms, but the different atoms occur only in the second-nearest neighbors sites. As a result it creates a very little different in the core binding energy. Therefore, 4H-Silicon Carbide has two binding energy for the nitrogen donor atoms, which has consequences on the obtained designing devices. 6H-Silicon Carbide has three energy levels of nitrogen atom and 3C-Silicon Carbide has only one energy level of nitrogen atoms. There are more complex polytypes, they are rhombohedra i.e., 15R-Silicon Carbide which has no less than of five binding energies, which are uniformly identified.

A photoluminescence technically called as PL spectrum as shown in Figure 8, show the number of lines that are related to the nitrogen bound atoms excitons and also for free excitons. Silicon Carbide has a band gap which is indirect, thus results into the related luminescence which is often assisted by the phonon atoms. Bound excitons is also a luminescence without having the phonon assistance, however this can occur because of conservation in the momentum, can also be accomplished with the nitrogen atom in the nucleus. Therefore the zero phonon lines which are on the nitrogen atom can be seen and denoted as P0 and Q0 respectively. From left to right it represents, 4H-SiC, 6H-SiC, and 3C-SiC, h and k denote crystal symmetry points that are hexagonal and cubic respectively.
Figure 8: The above Figure represents the near-band-edge phenomenon of photoluminescence spectrum that has the atoms of 4H-SiC.

The binding energies are represented as $E_D$, for both cubic and hexagonal nitrogen impurities which are equal to 102 meV and 59 meV respectively [12]. As per the effective mass approximation [13], the binding energy of an electron can easily bound to the nitrogen atom in 4H-Silicon Carbide would be represented with following equation:

$$E_D = 13.6 \left( Z^2 \cdot m^*/n^2 \cdot m_0 \cdot \varepsilon_r^2 \right) \text{eV} = 6.07\text{meV}$$

Where $m^*$ can be represented as the effective mass,

$\varepsilon_r$ is the dielectric constant,

$Z$ is the charge of an electron which is equal to 1 in the above example and

$n$ is the integer and also equal to 1 for the existing ground state.

This type of discrepancy can occur only between the actual main binding energy which is around 59 meV, and the effective mass. The correction voltage of the central cell is around 53 meV. But the defects that occur with large central cell correction will have wave functions which are much localized. If the larger the correction occurs the more the localization of the wave function, the probability of interaction between the each core will also be higher or between the each central cell and this type of electron can be the excitons only bound to the excited defect. Hence this is the main reason why the existing $Q0$ line is much bigger than the $P0$ line in that
spectrum. Here there is one more useful feature of the electric photoluminescence that it does not limit to the silicon carbide. But an apparent of SiC which is in the ratio of between the bound excitons luminescence and also of free excitons gives the accurate determination of level doping at once which is properly calibrated [13].

Since the correction of the central cell is much higher than the nitrogen defects in a cubic site which is a hexagonal site. In every perfect pure crystal, the hole-electron pairs can easily created through the absorption of bandgap photons that can be bind together to form the free excitons. These will results to move freely in the crystal state until the recombination occurs and can easily generate some part of light in the recombination process. If we want do the same process in a crystal state with some part of nitrogen in it, then there form the free excitons. Some parts of free excitons will lost some of its energy and then bind to center of its defect into a four-particle complex known as the bound excitons. This obtained four particles can form the electron-hole pair in the free excitons. This bound excitons will also cause the recombination to emit light as a new light source. Thus, the ratio between the bound excitons luminescence and free excitons has been compared and the doping level can also be determined. Here the free excitons cannot be seen by comparing the P0 line and the Q0 line. This can be seen only in very high doping range.

2.3 PROPERTIES OF SILICON CARBIDE

Since there are slight variation in the material properties of silicon carbide compared to different manufactured technologies in the material property which are presented below in detailed. The properties mainly focused on space applications. Thus Sintered Silicon Carbide materialistic properties, Boostec Sintered Silicon Carbide material properties [14], and Carbon felt Silicon Carbide material properties are interrelated to each other of the material properties [15]. Some of the cases, the obtained information is completed only with the gathering effect of data from the Touloukian [16], [17] and [18].

The properties which are given for the CVD Silicon Carbide are only based upon the information from the both Haas and Rohm [19]. In this study, there are two other brands for Silicon Carbide, which had been required only for the purpose of testing. They are Xycarb Carbon felt Silicon Carbon and Hexoloy SA Sintered Silicon Carbide [20]. Upon further discussion we can see more details of this study.

2.3.1 Mechanical properties

The most important and the basic properties of Silicon Carbide is mechanical property, which is having the functions such as Elastic modulus and density which has been compared to different materials in the previous case. The properties which are not important for the
mechanical properties are much more important for the Opto mechanical properties. Among all the properties that are needed to this mechanical properties, resulted in a good analysis for the Opto mechanical design. Almost at all room temperature these mechanical properties are having three different types of Silicon Carbide and they are useful for the BAM system application which is shown in Table 1.

In Silicon Carbide, the mechanical properties operate at room temperature and can be easily assumed at a constant temperature ranging from 100 K – 350 K, only because the trajectory in the temperature for these Silicon Carbide and their types, will not undergo any changes in the composition of crystallographic. The CVD Silicon Carbide has a density of 3.21*10^3 kg m^-3. The practical density of C/SiC and SSiC is much lower than the theoretical calculated density, and it is in the order 2% and 3% respectively. The Carbon felt Silicon Carbide is only responsible for the elastic modulus which are strongly reduced. As we know the Poisson ratio of fused silica and Silicon Carbide materials is equal to the 5.88% which is much lower than the brittle metals which is equal to v=0.34.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>SSiC</th>
<th>C/SiC</th>
<th>CVD SiC</th>
<th>Fused silica</th>
<th>TiAl5V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>[×10^3 kg m^-3]</td>
<td>3.1</td>
<td>2.55</td>
<td>3.21</td>
<td>2.2</td>
<td>4.4</td>
</tr>
<tr>
<td>$E$</td>
<td>[×10^9 N m^-2]</td>
<td>420</td>
<td>218</td>
<td>460</td>
<td>72</td>
<td>114</td>
</tr>
<tr>
<td>$\nu$</td>
<td>[-]</td>
<td>0.16</td>
<td>0.17</td>
<td>0.18</td>
<td>0.17</td>
<td>0.34</td>
</tr>
<tr>
<td>$\sigma_C$</td>
<td>[×10^6 N m^-2]</td>
<td>3000</td>
<td>?</td>
<td>2500</td>
<td>1100</td>
<td>970</td>
</tr>
<tr>
<td>$\sigma_T$</td>
<td>[×10^6 N m^-2]</td>
<td>200</td>
<td>130</td>
<td>?</td>
<td>50</td>
<td>880</td>
</tr>
<tr>
<td>$\sigma_B$ (3-pt)</td>
<td>[×10^6 N m^-2]</td>
<td>450</td>
<td>180</td>
<td>470</td>
<td>80</td>
<td>880</td>
</tr>
<tr>
<td>$m$</td>
<td>[-]</td>
<td>10</td>
<td>17</td>
<td>11</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>[×10^6 N m^-3/2]</td>
<td>3.5</td>
<td>2.3</td>
<td>?</td>
<td>0.8</td>
<td>75</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>[J m^-2]</td>
<td>14.2</td>
<td>23.6</td>
<td>?</td>
<td>4.3</td>
<td>-</td>
</tr>
<tr>
<td>$K$</td>
<td>[×10^12 N m^-2]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Shows the different Mechanical properties of Silicon carbide and the other materials which are related to it at room temperature

Table 1 above shows the tensile strengths, compressive strengths and bending strengths for different materials. Table 1 also shows that the compressive strengths of the given types of
Silicon Carbide are much greater than that of bending and tensile strengths of sintered SiC, which implies brittleness.

Since the reliability of the transistor is important, the material's weakness is required to be detected. Weibull flow statistics is the method of determining the materials property.

Here we can note that the data that can be obtained on the different Silicon Carbide in the below Table 2 and also from the Figure 9 and Figure 10 is very scattering. But, we cannot give any conclusion upon the temperature dependence on loading conditions or Weibull modulus, because there is no information that is available on the resultant flaw distribution and also the number of samples tested.

Figure 9: Weibull diagram for Boostec SSiC [23].
Table 2: Scaling stress and Weibull modulus for the plots of Figure 9 and Figure 10.

Silicon Carbide has a capability to resist much high stress level while comparing with the tension or bending in all ceramics. In the case of compressive loading, this failure probability was not applied by any type of sub-critical crack growth [22]. But, for tensile loading, this sub-critical crack growth is the main determining factor for the failure.

2.3.2 The Thermal Properties

Boostec SiC and Poco Carbon filled SiC can withstand the temperature changes from 100K to 350K [26 - 29]. The coefficient of thermal expansion of SiC is directly proportional to the temperature. As the temperature increases from 100K to 350K, Boostec SiC and Poco
Carbon filled SiC thermal coefficients increase at a rate of $2 \times 10^{-6}$ per Kelvin. This indicates the extremely low mechanical susceptibility of SiC based devices to change in temperature.

Figure 11: Coefficient of thermal expansion with respect to temperature

Figure 12: Thermal expansion from 293 K with respect to temperature

When we are looking at the thermal expansion at a room temperature for the data, Boostec Sintered Silicon Carbide can only show the small length change over a range of
temperature from 293 K to 100 K. This thermal conductivity data are also available for Boostec Sintered Silicon Carbide (Figure 13) but not for the Xycarb or Poco Carbon felt Silicon Carbide. Therefore the thermal conductivity of different Silicon Carbide material shows a very large spread for the large influence in additive materials of this property.

Figure 13: The plot shows temperature and thermal conductivity characteristics [25]

The data that is present on the specific heat of Boostec Sintered Silicon Carbide and Poco Carbon felt Silicon Carbide will not be available readily. However the Touloukian shows there is a specific heat upon several types of Sintered Silicon Carbide which is very similar to Figure 14. When combining all the Boostec Sintered Silicon Carbide and Touloukian data, a plot will appear on thermal stability which is a function of temperature can be represented on Figure 15. Here we have to mainly consider the thermal stability as large as possible. Thus the resultant plot shows that the thermal stability which is exponentially increased with the decrease of
temperature, which is very beneficial and good for the stability of the Basic Angle Monitoring (BAM) Opto-Mechanical Assembly system section of a cryogenic fiber collimator being developed by Boostec. The system will operate at a temperature of about 100 K.

![Graph showing volumetric thermal stability of Sintered Silicon Carbide with respect to temperature (data from Boostec and Touloukian combined)](image)

Figure 15: Volumetric thermal stability of Sintered Silicon Carbide with respect to temperature (data from Boostec and Touloukian combined)

The two thermal situations which are beneficial for the BAM system are:

1. The thermo-elastic behavior in the BAM system are critical from 293 K to 100 K cool down. During the cool down process, the optical components may not lose the alignment with respect to the other components.
2. This thermo elastic behavior of the BAM system, allows for a maximum variation of about ± 0.1 mK. Due to this type of very small thermal variation, the change in the mechanical alignment of the system of components should be minimal.

The length of change of dimension for the given working temperature variation for the existing two types of Silicon Carbide, TiAl6V4 and fused silica are shown in Table 3. This table will be used in further study to make the actual measurement of the stability in the BAM system.
2.3.3 Optical Properties:

Silicon Carbide (in alpha case) is a birefringent and its crystal structure can be determined as $N_c$ and $N_o$, where $N_c$ and $N_o$ are called the birefringence. Under the high temperatures and high pressure this can be partially transparent which is ranging from 100 – 800 nm of Silicon Carbide crystal growth. Moissanite also has alpha Silicon Carbide structure. CVD Silicon Carbide which is not transparent and has a refractive index which is equal to 2.63 and thus not birefringent. The reflectivity of Silicon Carbide in this visible spectrum is shown in Figure 16. The reflectivity is independent to the wavelength and crystal structure of the light. It is around 20 % [30] and [31]. As the reflectivity of the infrared light increases to 40 % there is a low reflectivity in Silicon Carbide, which is often coated with reflective metallic layer in a more quantity, such as gold or silver. Gold does not suitable well to Silicon Carbide [30].

Table 3: Thermal expansion of Sintered Silicon Carbide, Carbon felt Silicon Carbide, TiAl6V4 and fused silica for a temperature change of 293 K to 100 K and the coefficient of thermal expansion at 100 K.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L_{293-100K}$</td>
<td>$-2.0 \times 10^{-4}$</td>
<td>$-2.5 \times 10^{-4}$</td>
<td>$-0.13 \times 10^{-4}$</td>
<td>$-15.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\alpha_{100K} \left[ \text{m m}^{-1} \text{K}^{-1} \right]$</td>
<td>$0.5 \times 10^{-5}$</td>
<td>$0.25 \times 10^{-6}$</td>
<td>$-0.53 \times 10^{-6}$</td>
<td>$7.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Delta L_{+0.1 \text{mK @ 100K}}$</td>
<td>$5.0 \times 10^{-11}$</td>
<td>$2.5 \times 10^{-11}$</td>
<td>$-5.3 \times 10^{-11}$</td>
<td>$71 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
Figure 16: Reflectivity of Silicon Carbide in the visible spectrum

The Figure 17 below shows the absorption coefficient versus wavelength. In the optical properties of silicon measure at 300K temperature the wide range of wavelengths is given in the plot and the silicon solar cells typical operate from 400 to 1100 nm.

Figure 17: Absorption coefficient versus wavelength

The Figure 18 below shows the transmittance versus wavelength. Here internal transmittance refers to the transmittance that can be measured by excluding the reflection losses at the
entrance and exit surfaces of a glass Optical glasses can produce an excellent transmittance from the visible region to the near IR region.

Figure 18: Transmittance versus wavelength
3.1 MESFET

Metal Semiconductor Field-Effect Transistor (MESFET) has many high performance applications in microwave domain and the RF amplifiers. When transistors were first invented (bipolar junction transistor or BJT), the principle of field effect transistor (FET) was also investigated. BJTs then dominated semiconductor technology in the early days of microelectronics, starting from 1949.

The initial development of field effect transistor in practical form occurred in 1953. Since then, this semiconductor technology has been heavily developed and has resulted in the development of many technologies for production of pure semiconductor materials and related production techniques. The ability to produce the quality layers of oxide became critical due to high quality oxide layers being mandatory for proper MOSFET function. With these developments in the electronic semiconductor technology the first MOSFET was produced in 1960.

In addition to this development of semiconductor technology there are other devices such as Gallium Nitride FETs, Gallium Arsenide FETs and silicon carbide FET's. These devices mainly offer a very high frequency capability and low noise. The development of first MESFETs was done in 1966, and the extraordinary high frequency and Radio Frequency microwave performance were demonstrated a year later.

3.2 MESFET TYPES:

There are mainly two types of MESFET explained below:

1. Enhancement MESFET
2. Depletion MESFET

The Enhancement MESFET also known as n-channel MEFET, in which all devices will remain in off state and the entire channel is covered with other region called depletion. Since this region is much narrower, as a result the channel gets more expandable. Therefore there is a facilitation in the flow of carriers. The device that conducts the flow of current increases the channel width [32].
In depletion MESFET, which is also known as p-channel MESFET, the gate voltage changes with respect to the depletion region. Here the carrier flow is getting stopped by a non-positive voltage at gate and source terminal. Therefore this depletion region gets expanded between the gate and channel, a reverse biased junction voltage is formed, as a result pinch off is achieved i.e., it acts like a switch at that point. Therefore resistance between the source and drain terminal is very high at this point. [33]

The changes that are applied to the field is achieved only by changing the potential voltage, which results to the rise of three different regions in the I-V characteristics namely:

(i) Linear Region
(ii) Saturation Region and
(iii) Pinch-off Region.

3.3 MESFET STRUCTURE AND CHARACTERISTICS

The basic structure of MESFET is shown in Figure 19:

![Basic structure of MESFET](image)

Figure 19: Basic structure of MESFET

The depletion region in the Figure 19 is formed by the schottky contact at the gate terminal. Therefore this device will behave as a switch or a current controller. Majority carrier devices have much less scattering effect compared to minority carrier devices (such as MOSFETs), which are therefore capable of very high speed modulation [34] [35]. A typical plot of Current versus Voltage (I-V plot) for a MESFET is shown in Figure 20 below.
Figure 20: I-V characteristics of MESFET

In the above Figure 20, the drain current which is on x-axis i.e., $I_{DS}$ is plotted against drain voltage $V_{DS}$. The gate-source voltage is a function of drain current. As a result the individual curve represents the dependency of $I_{DS}$ versus $V_{DS}$ for the certain values of $V_{GS}$. The above figure 20 represents a type of mode operation in MESFET called the breakdown mode which can result in excess drain-source voltage.

3.4 SIC MESFET STRUCTURE AND CHARACTERISTICS

The structure of silicon carbide MESFET which is adopted for many applications is shown in below Figure 21
In this study, we are only dealing with the current-voltage and transconductance characteristics of silicon carbide MESFET’s [36].

The typical I-V characteristics and transfer characteristics are shown in the below Figure 22 (a) and (b). The detailed operation of these characteristics are studied in chapter 5

![Figure 22(a): I-V Characteristics of the SiC MESFET’s and Figure 22(b): Transfer Characteristics of SiC MESFET's](image)

3.5 FABRICATION IN MESFET

The complete MESFET fabrication process is described below in categories as shown in Figure 21. They are schedule in four different mask. These four mask levels are as follows [38] [39] [40]:

1. Implantation of Channel
2. Implantation of Source or drain
3. Contact formation in ohmic and
4. Gate formation of the Schottky.

All of this masks are used as positive resist in this process.

Steps of fabrication are as follows:

- The wafer should be cleaned.
- With a cap thickness of 100 nm make a deposition using Silicon nitride by reactive sputtering.
The patterning resist for the channel implant is made using positive resist with a thickness of 1.6 μm.

Silicon nitride in shallow etching for registration purposes in the alignment.

The buffering Hydrogen Fluoride solution and also the etching of plasma.

Ashing stripping in plasma consisting of oxygen.

With a target resist thickness of 0.8 μm resist the patterning for drain and source implant by using of resist in positive.

In source and drain regions the silicon ion implantation with a ion energy of 200 keV maximum, ion species of Silicon in ionized in single fashion and greater than $1 \times 10^{13}$ /cm² dose.

Ashing stripping in plasma consisting of oxygen.

The process of annealing of the implanted ions of using thermal annealing which is very rapid with the specifications of as follows:

1. Maximum temperature of 850 °C
2. Ambient as forming gas
3. Time is equal to 1.5 to 2 minutes

The patterning resist for the contacts containing ohmic formations with resist thickness of target is 0.8 μm.

CF4 etching plasma to the semiconductor surface

SiN etching in contacts containing ohmic.

Finally with a wet etch cleaning which is exposed GaAs surface at a solution of 50 %HCl.

The AuGe/Ni metal deposition in the contacts containing ohmic.

Electric beam evaporation and a technique called patterning.

Contacts which contain Ohmic that are alloyed in thermal heating with temperature of 475 – 500 °C maximum, ambient should be forming gas and at a time of 2 minutes.

Patterning resist for the etching of nitride in gate formation of Schottky with a resist thickness of 1.6 μm in target.

The Schottky gate formation for the silicon nitride etching.

CF4 plasma etching in the semiconductor surfaces.

Finally, cleaning with wet etch which is exposed to 50 %HCl solution of GaAs surface.

The deposition of aluminum metal in the gate formation of schottky, using an evaporation of electric beam with the technique called patterning.

The MESFET fabrication process overview using four masks and implantation process of double ion is shown in Figure 23.
Figure 23: Fabrication process of MESFET
3.6 ADVANTAGES, DISADVANTAGES AND APPLICATIONS OF MESFET’s:

The main advantages of using this MESFET are given below [41]:

- High Saturated Electron Velocity
- Chemically Inert
- High Breakdown Electric Device
- High Melting Point
- Wide Energy Band Gap Device
- High Electrical and Thermal Conductivity

The disadvantage of using MESFET structure is only due to the presence of the Schottky metal gate. Therefore it limits the forward bias voltage ($V_{bi}$) on the gate side. Therefore, the turn-on voltage must be greater than the threshold voltage.

The main applications of the MESFET are:

- High Frequency
- Wireless Communication
- Power Amplifiers
- Microwave Circuits
- High Power
- The use of MESFETS for high power electronic applications in the automotive industry [42].

The comparison between MESFET and MOSFET is:

MOSFET- Enhancement mode (normally off) and has a threshold voltage of 0.6V for N-MOSFET
MESFET- Depletion mode (normally on) and has a threshold voltage of -0.6V for N-MESFET
MOSFET- Minority carriers and inversion channel, it is self-aligned
MESFET- Majority carriers and depletion channel, it is not self-aligned
4.1 SILICON CARBIDE MESFET

Figure 24 below represents the equivalent circuit of a silicon carbide MESFET. At high drain voltages the channel becomes saturated and the electron velocity reaches the saturation velocity.

The entire region is divided into three different regions. In Regions I and II, the electron velocity is lower than the saturation velocity ($V_s$), since the electric field is low at the gate region. As the carriers move from source to drain, the electron velocity increases and subsequently reaches the saturation velocity. Therefore, the saturation region can be considered to start from the point where the carriers have reached $V_s$. The electric field in the saturation region is called the Saturation Electric Field ($E_s$). The region below saturation is called the Ungated Saturation Region (Region III).

The ohmic contacts are created to form source and drain terminals. The gate with the recessed structure is formed on the n-type SiC channel with a Schottky contact, and the low p-type doping layer (as a buffer) and SiC substrate are underneath the channel sequentially.

![Cross-sectional view of silicon carbide MESFET](image)

**Figure 24**: The cross-sectional view of silicon carbide MESFET showing the three regions in high drain voltage.
In Figure 24, $R_{dc}$ is called parasitic source resistance or parasitic drain resistance. This is included in the MESFET resistance for the contact resistances only under drain and source regions. The definition of source resistance is $R_S = R_{dc} + R_{S0}$. Here $R_{S0}$ is a function of $V_{GS}$. The drain resistance ($R_D$) is defined by: $R_D = R_{dc} + R_{D0}$.

A space charge is formed between the n-channel and the p-buffer. The p-buffer layer prevents the transportation of the electrons from the trap centers (defects) in the substrate. It also prevents the leakage phenomenon due to extra electrons in trap region.

In order to prevent the leakage phenomenon, it is necessary to use incomplete ionization of the dopants.

4.2 I-V CHARACTERISTICS

One dimensional Poisson’s equation may be expressed as

$$\frac{\partial^2 \varphi(y)}{\partial y^2} = -\frac{q N_d^+}{\varepsilon_s}$$ (1)

Where $N_d^+$ = ionized donor impurity concentration.

The ionized donor impurity concentration ($N_d$) is obtained as

$$N_d^+ = \frac{N_C}{2g} \exp \left( -\frac{E_D - E_C}{k_B T} \right) \ast \left( 1 + 4g \frac{N_d}{N_C} \exp \left( \frac{E_D - E_C}{k_B T} \right) - 1 \right)$$ (2)

Where $N_C$ = Effective density of states in conduction band
$g$ = Ground state degeneracy of the donor impurity level
$E_D$ = Donor energy level
$E_C$ = Conduction band
$k_B$ = Boltzmann constant
$T$ = Temperature

The channel potential, $\varphi(y)$ is defined as

$$\varphi(y) = -\frac{q N_d^+}{2 \varepsilon_s} y^2 + \frac{q N_d^{+b}}{\varepsilon_s} y + V_{gs} - V_{bl}$$ (3)

Where $b$ = depletion width and can be defined as

$$b(x) = \sqrt{\frac{2 \varepsilon_s}{q N_d^+}} [V(x) - V_{gs} + V_{bl}]$$ (4)

Where $V(x)$ = channel potential at any point of $x$ in the channel.
The drain current \(I_d\) can be evaluated from gradual channel approximation as

\[
I_d = q\nu(x)N_dW[a - b(x)]
\]  

Where \(W\) = channel width and 
\(a\) = channel thickness

The electric field and field dependent velocity \((\nu-E)\) characteristics in Silicon Carbide can be evaluated by using Caughey Thomas model is given by the following equation 1 [44], [45].

\[
\nu(E) = \mu(E)E(x) = \frac{\mu_0 E(x)}{1 + \frac{\mu_0 E(x)}{\gamma \nu_s}}
\]  

Where \(\gamma\) = fitting parameter and \(\mu_0\) is the low field mobility

The low electric field mobility \(\mu_0\) is defined as

\[
\mu_0 = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left(\frac{N_d}{N_F}\right)^a}
\]  

Where \(\mu_{\text{min}}\) = minimum mobility 
\(\mu_{\text{max}}\) = maximum mobility and 
\(N\gamma\) = fitting parameter

The substitution parameters \(u_0\) and \(u_1\) are defined as

\[
u_0 = \frac{b_0}{a} = \frac{1}{a} \sqrt{\frac{2\varepsilon_s}{qN_d} \left(V_{bi} - V_{gs} + I_c R_s\right) = \frac{\sqrt{V_{bi} - V_{gs} - I_c R_s}}{V_p}}
\]  

\[
u_1 = \frac{b_1}{a} = \frac{1}{a} \sqrt{\frac{2\varepsilon_s}{qN_d} \left(V_{ds} + V_{bi} - V_{gs} - I_c R_D\right) = \frac{\sqrt{V_{ds} + V_{bi} - V_{gs} - I_c R_D}}{V_p}}
\]

Where \(b_0\) = depletion width near the source 
\(b_1\) = depletion width near the drain and 
\(V_p\) = pinch off voltage

The pinch off voltage is defined as

\[
V_p = \frac{qN_d^+ a^2}{2\varepsilon_s}
\]  

In linear mode (non-saturation), the drain current \(I_d\) can be defined by substituting equation 8 & 9 and yields as
\begin{equation}
I_d = \frac{I_p[3(u_1^2-u_0^2)-2(u_1^3-u_0^3)]}{1+z(u_1^2-u_0^2)}
\end{equation}

Where \( Z = \frac{qN_D^2a^2\mu_0}{2\varepsilon_oLy_{v_s}} \) \hspace{1cm} (12)

\begin{equation}
I_p = \frac{q^2N_D^2\mu_0W a^3}{6\varepsilon_oL}
\end{equation}

Then the final form of I-V characteristics equation is evaluated as:

\begin{equation}
I_d = \frac{qZ\mu a N_d}{L}(V_{ds} - I_{ds}(R_s + R_d)) - \frac{2}{3V_p^2}\left[(V_{bi} - V_{gs} + V_{ds} - I_{ds}R_d)^{3/2} - (V_{bi} - V_{gs} + I_{ds}R_d)^{3/2}\right]
\end{equation}

Where \( I_d = \) drain to source current

\( V_{DS} = \) drain - source voltage.

\( Q = \) charge of an electron

\( N_D = \) donor concentration

\( a = \) active channel thickness

\( u = \) mobility of an electron

\( N_A = \) acceptor concentration

\( V_p = \) pinch off voltage (constant)

\( Z = \) gate width

\( L = \) gate length

\( R_s = \) parasitic source resistance

\( R_d = \) drain resistance

\( V_{BI} = \) built-in voltage

\( n_i = \) intrinsic concentration

\( V_{GS} = \) gate to source voltage (varying)

\( b_1 = \) depletion width near to the drain and

\( b_0 = \) depletion width near to the source
4.3 TRANSCONDUCTANCE IN SILICON CARBIDE MESFET

The reciprocal of resistance is called Transconductance which is the instantaneous ratio of the voltage at the input port and current at the output port which is represented as $g_m$ [49]. Transconductance is a critical performance parameter of any FET device, along with other important intrinsic parameters.

The generic equation for transconductance of MESFET device can be expressed as:

$$g_m' = \frac{g_m}{1+g_mR_s}$$

(15)

Where $R_s$ is the parasitic source resistance

The transconductance can be defined by differentiating drain current equation with respect to $V_{gs}$ keeping $V_{ds}$ constant and can be presented by the following equation:

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

(16)

However, the transconductance equation can be also determined by channel concentration, device width and velocity saturation effects [50] [51]:

$$g_m = \left(\frac{qN_PD_{er}}{2(V_b-V_{gs})}\right)^2 V_s W$$

(17)

Where $N_D$ = channel doping concentration

$W$ = Channel width and

$V_s$ = saturation velocity
Chapter 5  
Results & Discussion

An improved analytical three regions model is presented for short-channel SiC MESFETs. This model incorporates two region in the channel under the gate and a third region is a high field region between the gate and drain. This study shows the I-V characteristics of the SiC MESFET producing a tremendous impact in both saturation and non-saturation region.

Figure 25: Drain-source current (I_DS) versus drain-source voltage (V_DS) characteristics for different gate-source voltage (V_GS) and pinch-off voltage (V_p) constant.

The above Figure 25 presents the plot for drain-source current (I_DS) versus drain– source voltage (V_DS) for different gate-source voltage (V_GS) of 0V, -3V, -6V and -9V with the substrate concentration (N_a) of 1x10^{15} cm^{-3}, doping concentration of channel (N_d) of 1x10^{17} cm^{-3}, channel length (L) of 4x10^{-4}cm and constant pinch-off voltage V_p = 144.5V. The drain current linearly increases up to the V_DS = 50V and the non-linear properties of I-V characteristics clearly shows in the drain-source voltage range of 50 – 100V. The active channel thickness of 0.04x10^{-4}cm
was considered in the device structure and the obtained I-V characteristics showed the justified \( V_P \) value. The maximum \( I_{DS} \) of 350mA for drain-source voltage of 150V shows the device as a high power device. This I-V characteristic shown Figure 25 has been plotted by using Equation (14).

Figure 26: Drain-source current (\( I_{DS} \)) versus drain-source voltage (\( V_{DS} \)) characteristics for different pinch-off voltage (\( V_P \)) and constant gate-source voltage (\( V_{GS} \)).

The above Figure 26 shows a plot for the drain-source current (\( I_{DS} \)) versus drain-source voltage (\( V_{DS} \)) for different pinch off voltages (\( V_P \)) of 140V, 150V and 160V with constant gate-source voltage (\( V_{GS} \)) of 0V, substrate doping concentration \( N_A=10^{15} \text{ cm}^{-3} \), channel doping concentration of \( N_D=1\times10^{17} \text{ cm}^{-3} \) and channel length of \( L = 4\times10^{-4} \). The I-V characteristics shows linearity for the drain-source voltage range 0V to 50V and non-linearity for drain-source voltage range 50V to 150V. The maximum drain-source current of 430mA for the pinch-off voltage of 140V has been observed reflecting as a high power device. The displayed I-V characteristics for different pinch-off voltage shows a significant variation of drain current due to
different active channel thickness. This plot is important for studying the active channel thickness versus break-down voltage. The drain-source current for different pinch-off voltage has been plotted by using the equation (14) keeping gate-source voltage constant. The SiC MESFETs are employed for high power RF device, which is exceptionally better inherent quality of SiC MESFET compared to other field effect transistors (FETs) and bipolar junction transistors (BJTs). In order to understand the frequency performance, the transconductance has shown to play an important role in determining the frequency performance of a FET device.

The Figure 27 represents the transconductance (gm) versus gate-source voltage for different donor concentration (Nd) of 1x10^{16}, 7x10^{17} and 7x10^{18} cm^{-3}. The transconductance exponentially increases with the increment of gate-source voltage. Typically, the transconductance linearly increases with the increment of gate-source voltage V_{GS}. The
exponential effect of present transconductance plot shows an evidence of sub-threshold current. The threshold voltage is found to be approximately in the range of -6.8 to -7V for the channel doping range of $1\times10^{16}$ - $1\times10^{18}$ cm$^{-3}$. The properties of threshold voltage confirm the device working as depletion device as it is expected for SiC MESFET device. The transconductance has been plotted by using the equation (17).
CHAPTER 6
CONCLUSIONS

This study has been conducted for developing an improved analytical model of a short-channel Silicon Carbide MESFETs. The channel was divided into three regions, where the first region is influenced by the source, second region is influenced by the gate and partially by the source and the drain, and the third region is influenced by the drain. Because the drain region has a large potential drop at high drain voltages in a short channel device, therefore it can generally be ignored for accurate short channel analysis. Finally, using physics based analytical model, a simulation has been developed to study the current and voltage characteristics of Silicon Carbide MESFET.

The simulation of transconductance shows a non-linear increase with respect to gate to source voltage ($V_{GS}$) for a constant drain to source voltage ($V_{DS}$). The non-linear characteristics of the transconductance in SiC MESFETs show a clear indication of sub-threshold current due to gate leakage, which is significantly less compared to MOSFETs. Furthermore, the simulation results show that a SiC-based MESFET behaves as a depletion device, as indicated clearly in the transconductance plot.
REFERENCES

7. Bougoin, M. SiC material and technology for space optics. ICSO conference proceedings, 2000
16. Boostec, material properties leaflet, 2004
23. Bougoin, M. SiC material and technology for space optics. ICSO conference proceedings, 2000
26. Boostec, material properties leaflet, 2004
32. S.O. Kucheyev, J.S. Williams, C. Jag
34. http://nina.ecse.rpi.edu/shur/SDM2/Notes/Noteshtm/16MESFET
Appendix A

Q = charge of an electron
Epsilon = permittivity
\( N_d \) = donor concentration
A = active channel thickness
\( V_{ds} \) = drain to source voltage
U = mobility of an electron
\( N_a \) = acceptor concentration
\( V_p \) = pinch off voltage
Z = gate width
L = gate length
\( R_s \) = parasitic source resistance
\( R_d \) = drain resistance
\( V_{bi} \) = built-in voltage
\( V_{gs} \) = gate to source voltage
\( n_i \) = intrinsic concentration
\( I_{ds} \) = drain to source current
\( V_{sat} \) = saturation voltage
\( V_t \) = thermal voltage
Appendix B

MATLAB CODE

% GRAD THESIS ECE-698C
% Matlab code for the Silicon Carbide MESFET's
% Current and voltage characteristics in drain to source region where Vp is constant and Vgs is varying

clc;       % clear the command window
clear all; % clears all function, variables, workspaces etc
close all; % close all open files
q = 1.6*(10^-19); % charge of an electron
epsilon = 8.9*8.8542e-14; % EPS=Eo*Es
Nd = (1*(10^17)); % donor concentration
Na= 10^15; % acceptor concentration
ni= (5*(10^-9)); % intrinsic concentration
a = (40*(10^-6)); % active channel thickness
u = 500; % mobility of an electron
Vp = ((q*Nd*a*a)/(2*8.8542*10^(-14))); % pinch off voltage (constant)
Z = (100*(10^-4)); % gate width
L = (4*(10^-4)); % gate length
Rs = 5; % parasitic source resistance
Rd = 5; % drain resistance
loop= 100; % loop repeating
loop1 =0.000000001; % loop repeating
Vbi = 0.0253*(log((Nd*Na)/(ni*ni))); % builtin voltage
Vgs = 0; % gate to source voltage (varying)
Vds = [0:1:150]; % Vds value ranging from 1 to 10
Ids(1) = 0; % intially Ids is zero
for j=1:length(Vds)
    for i = 1:loop
        a1 = ((q*Z*u*Nd*a)/L);
        a2 = Ids(i)*(Rs+Rd);
        a3 = 2/(3*sqrt(Vp));
        a4 = (Vbi-Vgs+Vds(j)-(Ids(i)*Rd))^((3/2));
        a5 = (Vbi-Vgs+(Ids(i)*Rs))^((3/2));
        Ids (i+1)= ((a1)*(Vds(j)-a2-((a3)*(a4-a5))));
    end
end
result = abs((Ids(i+1)-Ids(i))/Ids(i+1));
if(result<loop1)
  res(j) = Ids(i+1);
  break;
end
end
res(j) = (Ids(i+1))*1000;
end
plot (Vds, res)
xlabel('Vds, drain-source voltage in volts'),
ylabel('Ids, Drain to source current in milli amperes'),
title('Vds-Ids characteristics of Silicon carbide MESFETs')
hold on;
Vgs = -3;
Vds = [0:1:150];
Ids(1) = 0;
for j=1:length(Vds)
  for i = 1:loop
    a1 = ((q*Z*u*Nd*a)/L);
    a2 = Ids(i)*(Rs+Rd);
    a3 = 2/(3*sqrt(Vp));
    a4 = (Vbi-Vgs+Vds(j)-(Ids(i)*Rd))^(3/2);
    a5 = (Vbi-Vgs+(Ids(i)*Rs))^(3/2);
    Ids (i+1)= ((a1)*(Vds(j)-a2-((a3)*(a4-a5))));
    result = abs((Ids(i+1)-Ids(i))/Ids(i+1));
    if(result<loop1)
      res(j) = Ids(i+1);
      break;
    end
  end
  res(j) = (Ids(i+1))*1000;
end
plot (Vds, res,'g')
hold on;
Vgs = -6;
Vds = [0:1:150];
Ids(1) = 0;
for j=1:length(Vds)
  for i = 1:loop
\[ a_1 = \frac{(q*Z*u*Nd*a)}{L}; \]
\[ a_2 = \text{Ids}(i) \cdot (R_s + R_d); \]
\[ a_3 = \frac{2}{(3*\text{sqrt}(V_p))}; \]
\[ a_4 = (V_{bi} - V_{gs} + V_{ds}(j) - (\text{Ids}(i) \cdot R_d))^{(3/2)}; \]
\[ a_5 = (V_{bi} - V_{gs} + (\text{Ids}(i) \cdot R_s))^{(3/2)}; \]
\[ \text{Ids}(i+1) = ((a_1) \cdot (V_{ds}(j) - a_2 - (a_3) \cdot (a_4 - a_5))); \]
\[ \text{result} = \text{abs}((\text{Ids}(i+1) - \text{Ids}(i)) / \text{Ids}(i+1)); \]
\[ \text{if} (\text{result} < \text{loop1}) \]
\[ \text{res}(j) = \text{Ids}(i+1); \]
\[ \text{break}; \]
\[ \text{end} \]
\[ \text{end} \]
\[ \text{res}(j) = (\text{Ids}(i+1)) \cdot 1000; \]
\[ \text{end} \]
\[ \text{plot} (V_{ds}, \text{res}, 'r') \]
\[ \text{hold on}; \]
\[ V_{gs} = -9; \]
\[ V_{ds} = [0:1:150]; \]
\[ \text{Ids}(1) = 0; \]
\[ \text{for } j=1:\text{length}(V_{ds}) \]
\[ \text{for } i = 1:\text{loop} \]
\[ a_1 = \frac{(q*Z*u*Nd*a)}{L}; \]
\[ a_2 = \text{Ids}(i) \cdot (R_s + R_d); \]
\[ a_3 = \frac{2}{(3*\text{sqrt}(V_p))}; \]
\[ a_4 = (V_{bi} - V_{gs} + V_{ds}(j) - (\text{Ids}(i) \cdot R_d))^{(3/2)}; \]
\[ a_5 = (V_{bi} - V_{gs} + (\text{Ids}(i) \cdot R_s))^{(3/2)}; \]
\[ \text{Ids}(i+1) = ((a_1) \cdot (V_{ds}(j) - a_2 - (a_3) \cdot (a_4 - a_5))); \]
\[ \text{result} = \text{abs}((\text{Ids}(i+1) - \text{Ids}(i)) / \text{Ids}(i+1)); \]
\[ \text{if} (\text{result} < \text{loop1}) \]
\[ \text{res}(j) = \text{Ids}(i+1); \]
\[ \text{break}; \]
\[ \text{end} \]
\[ \text{end} \]
\[ \text{res}(j) = (\text{Ids}(i+1)) \cdot 1000; \]
\[ \text{end} \]
\[ \text{plot} (V_{ds}, \text{res}, 'k') \]
\[ \text{hold on}; \]
\[ \text{hleg1}=\text{legend}('V_{gs}=0v', 'V_{gs}=-3v', 'V_{gs}=-6v', 'V_{gs}=-9v'); \]
% GRAD THESIS ECE-698C
% Matlab code for the Silicon Carbide MESFET’s
% Current and voltage characteristics in drain to source region where Vgs is constant and Vp is varying

clc; %clear the command window
clear all; %clears all function variables, workspaces, etc
close all; %close all open files
q = 1.6*(10^-19); % charge of an electron
epsilon = 8.9*8.8542e-14; % EPS=Eo*Es
Nd = (1*(10^17)); % donor concentration
Na= 10^15; % acceptor concentration
ni= (5*(10^-9)); % intrinsic concentration
a = (40*(10^-6)); % active channel thickness
u = 500; % mobility of an electron
Vp = ((q*Nd*a*a)/(2*8.9*(10^-14))); % pinch off voltage
Z = (100*(10^-4)); % gate width
L = (4*(10^-4)); % gate length
Rs = 5; % parasatic source resistance
Rd = 5; % drain resistance
loop= 100; % loop repeating
loop1 =0.000000001; % loop repeating
Vbi = 0.0253*(log((Nd*Na)/(ni*ni))); % builtin voltage
Vgs = 0; % gate to source voltage (constant)
Vp=140; % pinch off voltage (varying)
Vds = [0:1:150]; % Vds value ranging from 1 to 10
Ids(1) = 0; % intially Ids is zero
for j=1:length(Vds)
    for i = 1:loop
        a1 = ((Vp*2*8.9*(10^-14))*Z*u)/(L*a);
        a2 = Ids(i)*(Rs+Rd);
        a3 = 2/(3*sqrt(Vp));
        a4 = (Vbi-Vgs+Vds(j)-(Ids(i)*Rd))^(3/2);
        a5 = (Vbi-Vgs+(Ids(i)*Rs))^(3/2);
        Ids (i+1)= ((a1)*(Vds(j)-a2-(a3*(a4-a5))));
        result = abs((Ids(i+1)-Ids(i))/Ids(i+1));
        if(result<loop1)
            res(j) = Ids(i+1);
    end
end
break;
end
end
res(j) = (Ids(i+1))*1000;
end

plot (Vds, res)
xlabel('Vds, drain-source voltage in volts'),
ylabel('Ids, Drain to source current in milli amperes'),
title('Vds-Ids characteristics of Silicon carbide MESFETs')
hold on;
Vp=150;
Vds = [0:1:150];
Ids(1) = 0;
for j=1:length(Vds)
for i = 1:loop

%a1 = ((q*Z*u*Nd*a)/L);
a1 = ((Vp*2*8.9*(10^(-14))*Z*u)/(L*a));
a2 = Ids(i)*(Rs+Rd);
a3 = 2/(3*sqrt(Vp));
a4 = (Vbi-Vgs+Vds(j)-(Ids(i)*Rd))^(3/2);
a5 = (Vbi-Vgs+(Ids(i)*Rs))^(3/2);
Ids (i+1) = ((a1)*(Vds(j)-a2-((a3)*(a4-a5)));
result = abs((Ids(i+1)-Ids(i))/Ids(i+1));
if(result<loop1)
res(j) = Ids(i+1);
break;
end
end
res(j) = (Ids(i+1))*1000;
end

plot (Vds, res,'g' )
hold on;
Vp=160;
Vds = [0:1:150];
Ids(1) = 0;
for j=1:length(Vds)
for i = 1:loop

%a1 = ((q*Z*u*Nd*a)/L);
\[
a1 = ((Vp*2*8.9*(10^{-14}))*Z*u)/(L*a));
\]
\[
a2 = Ids(i)^*(Rs+Rd);
\]
\[
a3 = 2/(3*sqrt(Vp));
\]
\[
a4 = (Vbi-Vgs+Vds(j)-(Ids(i)^*Rd))^{(3/2)};
\]
\[
a5 = (Vbi-Vgs+(Ids(i)^*Rs))^{(3/2)};
\]
\[
Ids (i+1)= ((a1)^*(Vds(j)-a2-((a3)*(a4-a5))));
\]
\[
result = abs((Ids(i+1)-Ids(i))/Ids(i+1));
\]
\[
if(result<loop1)
res(j) = Ids(i+1);
break;
endif
\]
\[
res(j) = (Ids(i+1))*1000;
\]
\[
plot (Vds, res, 'r')
\]
\[
hold on;
\]
\[
hleg1=legend('Vp=140v','Vp=150v','Vp=160v');
\]

% GRAD THESIS ECE-698C
% Matlab code for the Silicon Carbide MESFET's
% Transconductance characteristics i.e. differentiating Ids with respect to Vgs where Nd is kept constant

clc;

clear all;

close all;

q = 1.6*(10^{-19});
epsilon = 8.9*8.8542e-14;
n = (1*(10^{17}));
Nd = (1*(10^{16}));
Na= 10^{15};
ni= (5*(10^{15}));
Vbi = 0.0253*\left(\log\left((Nd*Na)/(ni*ni)\right)\right) \quad \text{builtin voltage}
Vs = 2*(10^{7}) \quad \text{saturation velocity}
W = 1000*(10^{-4}); \quad \text{gate width}
Vgs = [-7:1:0]; \quad \text{Vgs value ranging from -20 to 0}

for i=1:8
Vbi = 0.0253*\left(\log\left((Nd*Na)/(ni*ni)\right)\right);
a1 = q*n*epsilon;
a2 = Vbi-Vgs(i);
a3 = ((a1/(2*(a2))))^{(1/2)}
gm(i) = a3*Vs*W;
end
plot(Vgs,gm);
xlabel('Gate-source voltage in volts'); ylabel('Transconductance in ms/mm');
title('Variation of transconductance with respect to gate-source voltage');
hold on;

Nd = (7*(10^17)); % donor concentration
Vgs = [-7:1:0]; % Vgs value ranging from -20 to 0

for i=1:8
    Vbi = 0.0253*(log((Nd*Na)/(ni*ni))
    a1 = q*n*epsilon;
    a2 = Vbi-Vgs(i);
    a3 = ((a1/(2*(a2))))^(1/2)
    gm(i) = a3*Vs*W;
end
plot(Vgs,gm,'g');

Nd = (7*(10^18)); % donor concentration
Vgs = [-7:1:0]; % Vgs value ranging from -20 to 0

for i=1:8
    Vbi = 0.0253*(log((Nd*Na)/(ni*ni))
    a1 = q*n*epsilon;
    a2 = Vbi-Vgs(i);
    a3 = ((a1/(2*(a2))))^(1/2)
    gm(i) = a3*Vs*W;
end
plot(Vgs,gm,'r');
hleg1=legend('Nd=1*10^16','Nd=7*10^17','Nd=7*10^18');