ON SCALING OF AN ION IMPLANTED GALLIUM NITRIDE MESFET

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For the degree of Master of Science

In Electrical Engineering

By

Anish Vemulapalli

May 2016
The graduate project of Anish Vemulapalli is approved:

_________________________________________  
Dr. Jack Ou  

_________________________________________  
Professor Benjamin Mallard  

_________________________________________  
Dr. Somnath Chattopadhyay, Chair  

California State University, Northridge
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Abstract

ON SCALING OF AN ION-IMPLANTED GALIUM NITRIDE MESFET

By

Anish Vemulapalli

Master of Science in Electrical Engineering

The main objective of this grad project is to study the scaling effect of different electrical parameters of GaN base MESFET by using a physics based analytical model using simulated MATLAB. The device dimensions, doping concentration and fabrication parameters have been scaled to determine the scaling effect on the drain to source current, threshold voltage, cutoff frequency, time delay and dc output power. The purpose of this grad project also serves how the scaling effects the device parameters having a positive impact on device fabrication and also the anticipated scaling results may get saturated beyond some point of scaling in the device. The grad project incorporates the introduction in chapter one, GaN material in chapter two, MESFET physics in chapter three, scaling rules in chapter four, numerical equations in chapter five and results and discussion in chapter six.
Chapter 1: Introduction

In the present modern world, wide bandgap semiconductors has gained the importance because of their potentials for use in wide variety of high frequency and high power devices [1]. These devices have more electric field due to wide bandgap, distinct material properties and high drift velocity of electron which made these devices suitable for high frequency and high power applications. In this situation these devices made the market to develop microwave amplifier for increasing wireless communication. In this process several research works are done on Gallium Nitride (GaN) Metal semiconductor field effect transistor’s (MESFET’s) when compared to Heterojunction field effect transistor’s (HFET’s). Generally MESFET’s epilayer are easy to realize and physical effects can be interpreted because it has no piezoelectric strain effects and heterojunctions.

1.1 Frequency performance of devices

Generally GaN devices are used for high power microwave circuits. Gallium Nitrate with low field mobility of $1500 \text{cm}^2/\text{Vs}$, bandgap energy of 3.4eV and low parasitic device values is suitable for high frequency and high power device applications. When GaN is grown on silicon carbide a thermal conductivity of 4.5W/cm/K which makes the device suitable for high power application. Molecular beam epitaxy method is used to grow GaN epilayer using single crystal substrate [2]. Each and every step of the process is clearly monitored in the growth process. In order to obtain GaN Wurtzite crystal structure the surface should be smooth. This is achieved by rms that should be as low as 1.3nm. In order to obtain good electrical properties we use photoluminescence. Band edge is centered to 3.4eV with width of 5meV. This shows that GaN heteroepitaxially grows on diamond. This can be used for high power applications.

Recent investigation on GaN MESFET’s device shows that a semiconductor device with cut-off frequency of 850MHz will deliver an output of 48.5W with a better power efficiency of 75% [3]. In the same way another group of researchers found some interesting facts on the GaN MESFET’s device. GaN device with an output power of 5W, power added efficiency 30% at $V_d = 46 \text{ V}$ with cut-off frequency of 650MHz was achieved [4]. GaN MESFET with dimensions 0.5um*150um has been reported. This device has Cut-off frequency of 5GHz and PAE of 35% gives good output power [5].
Another research investigations on threshold voltage ($V_t$) are being reported. Threshold voltage of GaN MESFET prove that a GaN device range between 5v to 25v, Drain current of 250mA/mm, Transconductance upto 50mS/mm are suitable for high frequency applications [6]. A GaN MESFET device with gate to source spacing of 1um, drain to source spacing of 2.5um, length of gate 0.3um, and gate width of 2*50um specifications were simulated and results are observed. This results shows maximum cutoff frequency at 10GHz [7]. Some researches with a gain of 8.5dB and cutoff frequency of 30GHz produces 1dB minimum noise figure [8].

Research work on fabrication of GaN MESFET were demonstrated. GaN MESFET devices with unity power gain and cutoff frequency, transconductance of 40ms/mm, PAE of 30% at Drain to Source voltage $V_{gs} = -2V$ and Drain to source voltage $V_{ds} = 25V$ at 5GHz gives maximum frequency of oscillation. The cutoff frequency values lies between 20GHz to 50GHz. These values record the highest frequency data in GaN MESFET’s [9]. A MESFET device with cutoff frequency 25GHz, output power of 300W was obtained with 0.45um gate GaN MESFET [10]. Fabrication of GaN MESFET’s device with cutoff frequency 12.6GHz, threshold frequency of 9.5GHz with transconductance of 150mS/mm gives power added efficiency of 30% at $V_{ds} = 2V$ [11].

Now a days GaN heterostructure is widely used in high power applications and gain a lot of attention in the semiconductors devices. The study of hot electron and energy flow is therefore an interesting part in the GaN systems. In application of electric field electrons gain energy and they try to be in equilibrium with photons, however equilibrium of each other through electron-electron interaction takes place. This leads to the formation of hot electron system and can find temperature variations that exceeds the lattice photons. The energy relaxation time is set by the emission of charge and acoustic. This shows the time for hot electrons to set to the lattice temperature. Using acoustic deformation potential scattering at a very low temperatures the cooling of emission can be stabilized. Polar photons dominate electron cooling at high temperatures above 100 K. Energy flows from photons to photons in the sapphire substrate in GaN lattice. As said earlier energy relaxation time is very important for the device design and concept of cooling of hot carriers also play’s a prominent role in device performance.
At high temperature and high power applications of microwave frequency GaN heterojunction FET’s are used because they offer high breakdown electric field of 4V/cm and bandgap of 3.4eV [12]. GaN HEMT’s with a power output up to 9.8W/mm at 8 GHz [13] has been demonstrated. A scientist named Daumiller [14] demonstrated the GaN FET’s that can operate up to 750°C using SiC as substrate. Low dielectric constant and high electron saturation velocity of $3 \times 10^7$ cm/s with low capacitance are the other factors that lead GaN based devices suitable for high frequency operation [15]. Gallium Nitride material has ideal devices characteristic properties and electrical properties which best suits for high power applications. Using GaN material many high frequency devices are fabricated that gain attention particularly in microwave frequency compared to other devices. For the operation of small signal, microwave devices are characterized by scattering and admittance parameters. S.S. Islam and A.F Anwar developed non-linear model of GaN MESFET’s using transconductance and resistance [16]. In order to achieve device model a scientist named Zhang [17] used neural networks physics to represents microwave and RF design of FET’s. Fixed biasing device models mostly use S and Y parameters. In other biasing conditions we have to extract equivalent circuit parameters using S parameters and it’s a time consuming process.

Although, GaN devices are used in the market these materials have some defects or problems. In absence of light current collision is observed and this tends to trapping of electrons at the channel interface. I-V characteristics determine the time intervals of current collapse. The current collapse is recovered by increasing the time interval and de-trapping of electrons. For the applied signal the trapping effect can be reduced by modelling the frequency dispersion of transconductance at output resistance. A mobile charge carrier can be trapped easily at the trapping centers. In order to remove the trapping centers first the defects must be detected. The trap centers usually occurs in case of damage. Performance of the device gets reduced at high frequency and high power application due to the trapping effect. A scientist named Zhang identified and reported the length of trapped charge region along the channel substrate interface. At the same time current collapse in GaN MESFET’s in absence of light is proposed by Klein. Both together presented a theoretical model which describes the restoration of collapsed current at low drain bias. Recovery of current collapse can be done by keeping a 10s time hold. As discussed earlier the trapping effects
reduce output resistance and transconductance values. Golio used an extra voltage
dependent RC circuit to reduce these defects. Mixed model circuits are incorporated at the
output terminals to reduce dispersion at the output resistance.

Wide bandgap semiconductors are used for high power electronic devices. Basically for
high speed and high power applications wide bandgap GaN based devices are used so that
they can tolerate to high heat in HBT’s. Mostly in GaN devices are used for switching in
high power and high temperatures. They are also used as power amplifiers in satellite
communications [18]. Electromechanical power devices cannot attain high standoff
voltages with Si based devices and with the development of wide bandgap power devices
and the implementation of GaN material made the devices to attain standard voltages.
Moreover the wide band gap devices have fast switching frequency in pulse modulated
inverters [19]. All microwave transmitters for radar communication uses wide band gap
semiconductor that are attractive for power electronics applications. Main applications are
in the primary distribution system ~100-2000kVA and subsidiary system of ~1-50MVA.

In the modern world due to the developing technology and the requirement of human needs
many high power RF amplifiers are discovered. In developing high power devices and
minimizing the wastage we implemented the kW level RF power source for energizing the
semiconductor structure [20]. In olden days the use of Radio frequency and microwave
was limited to drive amplifier [21]. Vacuum tube amplifiers are used to generate few
hundreds of watts that is sufficient for the RF and Microwave application devices. Now
with the advancement in technology the power level has crossed from kW level power
regime [22]. Although providing with clean power that is the power which is free from
spurious and phase noise these devices failure rate reported 3% per year. Various
advantages of Solid state power amplifier compared to vacuum tube is the development of
kW level power amplifiers. Single solid state power device has output power that is
different from other device that produces an output in order of few hundred of watts. High
power can be achieved by adding power outputs of multiple devices in form of modules.
This summing of devices is possible using power combiner and divider. In communication
pulse modulation can be expected from RF and microwave signals in some cases. To get a
good matching impedance network the power amplifier modules should be focused well.
Using incorporating radial strip line structure, external tuning mechanism and without isolating resistors easy model of the device can be constructed [23]. Teppati developed directional coupler method by eliminating the micro strip line [24]. Demonstration of solid state amplifier with power of 2kW, starting with a frequency of 350 MHz and 505 MHz has been developed. Moreover high power 8kW amplifier was developed by combining 16 power combiners. For all valid design procedures precise vector and scalar measurements were carried out. Continuing this, high power wave and RF pulse testing was carried out.

1.2 Optically controlled MESFET

OPFET abbreviated as Optical Field Effect Transistor has many advantages compared to other FET’s. In field of optoelectronics Gallium nitride semiconductor play a crucial role. Compared to Silicon carbide and other materials, Gallium nitride has wide band gap energy approximately 3.4eV at 300˚K [25]. These wide band gap semiconductor produces less noise so it suitable for making high sensitive detectors in Ultraviolet range. Moreover, thermal conductivity of Gallium nitride is high that is around 130W/mk compared to Silicon carbide [26]. This advantage makes the material suitable for high temperature devices and Gallium Nitride is good option for optoelectronic devices.

1.3 GaN optoelectronics

Using nitrogen doped GaN p-n junction a green LED was developed in the year 1968. During 1960’s and 1970’s many materials came into existence. The inventions of blue LED’s came with 6H-SiC with energy band gap of 3.0eV and GaN with energy gap of 3.4eV. The property of GaN makes it to allow a wide range of colors in fabricating LED’s using visible lights to ultraviolet rays. For high performance, laser are developed by using a combination of blue and violet colors. Generally speaking we observe LED’s in many applications that are related to our daily life. For instance people usually observe LED’s at traffic signal lights, LED’s are also used in computers to read and write data.

1.4 Importance of scaling technology

Scaling is important tool for device miniature. Scaling is performed on device parameters in order to improve the performance. Various constraints come into play while scaling. These are applied to both intrinsic as well as extrinsic device parameters. Sub threshold
circuit design is an important parameter to design low power applications [27]. In order to design a low power device using sub threshold must be scaled according to the scaling rules which are described further. While manufacturing a device we come across various disturbances like noise and delay in time. This can be overcome by using advanced scaling strategies. However, we explore many scaling rules beyond the conventional scaling path. In order to determine the performance of one dimensional FETs we make use of parasitic capacitance. In this we came out with possible device scaling path that concentrates on scaling of contacted gate pitch, which suits for improvement in performance for both circuit and design level [28].

The device performance depends on the speed of the device and scaling technology had made the device achieving for faster speed. Device scaling became the principal tool for technological innovations. Gate length depends upon various parameters like threshold voltage, output conductance, capacitance and transconductance. Experiments proves that shallow implant give better results but in addition to that vertical scaling of the devices is compulsory. The effort to build an integrated circuit device along with scaling continued in improvement of downsizing or reducing the increased device performance and density. New technical developments and limit in factors are examined that enable NMOS density to be compared with CMOS density. Many isolation techniques are discussed which influences the doping concentration and device performance are examined. The factors that affect the dielectric thickness are discussed. The predominant factor in the MESFET is diode capacitance that has several limiting factors which effects the device performance. The fabrication methods and metallization techniques along with scaling made the devices to look smaller and better [29].

MESFET technology is an advanced technology and is very attractive for high performance application devices. Here in this paper describes about MESFET technology, applications and limitations. First this paper discusses mainly on device scaling theory and projections, we analyze possible limits of MESFET technology and performance of device with respect to device physics. While designing the device we come up with many possible extensions and built a novel devices that best suits for our applications. Our analysis coves non data processing and data processing applications that suits for solid state electronic devices.
Moreover, this MESFET technology is the future for the next coming 15-20 years [30]. In order to obtain high power in the devices we mostly use 4H-Sic materials because of its high electrical properties. 4H-Sic is an indispensable material that has excellent physical properties.
Chapter 2: Overview of Gallium nitride material

Over the past few decades, III-nitrides have gained a rapid progress in device technology, material processing, and growth. Many attempts were made by great scientists to produce GaN material. This dream came true in 1932, where GaN was synthesized in powder form. After that, Hahn and Juza produced GaN in small needles. In the beginning stages, there was a very slow progress of GaN technology. In 1969 GaN is grown in large crystals on sapphire substrate. They used hydride vapor phase epitaxy for the development of single crystal GaN material. This technology is implied to single GaN templates [31]. (MOCVD) abbreviated as Metal organic chemical vapor deposition technology is used to grow GaN. In 1974 GaN was grown via molecular beam epitaxy (MBE). In 1972, a scientist named Pankove used Zn doping to produce first LED in blue. Later they started producing different colors like red, yellow or blue by varying the concentration of Zn doping in the light emitting region. They called this LED as a metal insulator n type (M-i-n) LED. In the year 1972 Maruska use Mg-doped diode to produce violet light [32].

Due to lack of lattice match substrate there was a poor epitaxial layer quality. The doping of these epilayers layers are always a unintentional doped n type resulting various growth defects. In the year 1983 Yoshida developed a two-step growth method to improve the quality of epilayers [33]. By means of MOCVD we came to know that a thin GaN layer can also be used as a buffer layer. Later other sophisticated methods like Lateral epitaxial overgrowth (LEO) and Pendeo epitaxial overgrowth (PEO) were introduced to improve the quality of the epitaxially grown GaN.

Until 1989 Materials with p-type conduction remained as the most outstanding issue even though there is a tremendous growth in GaN epilayer quality. They invented p-type GaN by passing low energy electron beam irradiation (LEEBI) [34]. By annealing GaN-Mg at 700°C in a vacuum can produce P-type GaN. The annealing method is the most efficient method for mass productions. Further p-type GaN can also be obtained by electromagnetic or UV wave radiation at a temperature of 400°C.

Achievement of p-type conduction and development of high quality GaN led to rapid development in the fabrication of GaN devices. In 1989 Amano developed the first p-n junction LED. By seeing this Nichia chemical industries released a luminous intensity of
l lumen and high efficiency of blue LEDs were launched [35]. In next few years a luminous intensity over ten lumen have been commercialized by using InGaN LEDs. Nakamura in Jan 1996 introduced the first working model of electric current injection based on GaN LDs [36].

During the time of light emitting diodes and optical laser diodes, various electronic devices were also fabricated using GaN material. In 1992, a scientist named Khan invented a two dimensional electron gas (2DEG) by using GaN/AlGaN heterojunction [37]. In the subsequent year Khan developed the first DC performance of GaN MESFET (metal semiconductor field effect transistor) [38]. A small signal measurements of AlGaN MESFET were reported. The first measured microwave power of 1.1W/mm was also reported at 2GHz using GaN HEMT [39] and X band power of 0.27W/mm was noticed. Dramatically power density of GaN HEMTs has slumped up. A company named Cree has observed a power density approximately 30w/mm at 7.5 GHz [40]. MMIC abbreviated as a monolithic microwave integrated circuit for amplifiers was reported in 1999. Shortly the first GaN/AlGaN HBTs and bipolar transistors were introduced. Common emitter current gain HBTs came into existence [41]. They started improving the current gains in HBTs by selectively regrown. Xing observed current gain as 35 at 300k and was reported. Zolper developed the first GaN junction field affect transistor was fabricated using ion implantation doping [41].

First, the development has initiated with the synthesis of GaN crystal in 1930s. During the past few decades there was a tremendous increase in the technology of GaN. During 1990s, we observed many advancements in process techniques, impurity doping, epilayer growth, etc. A wide variety of electronic and optical based GaN devices has been developed and commercialized. All the technical obstacles has been successfully overcome. In the field of optoelectronics with the invention of UV detectors, LDs and various color LEDs have established a significant role in this field.
2.1 Material properties of the device

In order to understand any electronic device performance first we need to know the fundamental properties of materials. The Table 1 below shows the material properties of various elements like GaN, SiC, GaAs/AlGaAs/InGaAs. A high bandgap energy has high electric breakdown fields which is responsible for high supply voltages. Moreover, it provides improved radiation hardness and can withstand at high operating temperatures. The bandgap of SiC and GaN is conventionally two or three times more compared to GaAs materials. Wide band gap materials have good electric breakdown fields than other semiconductors. Usually a material which has high saturation velocity, high mobility, high operating frequency and high currents is preferred. For instance, GaAs has high electron mobility that is why FETs fabricated from this material’s show good performance [42].

<table>
<thead>
<tr>
<th>Property</th>
<th>GaAs</th>
<th>AlGaAs/InGaAs</th>
<th>SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap Energy, Eg (eV)</td>
<td>1.43</td>
<td>3.26</td>
<td>3.44</td>
<td></td>
</tr>
<tr>
<td>Electric breakdown field (MV/cm)</td>
<td>0.4</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Saturated velocity electrons</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Vsat(Vpeak) 10^7 cm/s</td>
<td>(2.1)</td>
<td>(2.0)</td>
<td>(2.7)</td>
<td></td>
</tr>
<tr>
<td>Electron mobility, cm^2/v-s</td>
<td>8500</td>
<td>700</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------</td>
<td>-----</td>
<td>-----</td>
<td></td>
</tr>
<tr>
<td>2DEG density, (n_1)</td>
<td>&lt;0.2</td>
<td>NA</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>(1013 cm(^{-2}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, (k)</td>
<td>0.5</td>
<td>3.7 - 4.5</td>
<td>1.3 - 2.1</td>
<td></td>
</tr>
<tr>
<td>(W/cm(^{-2}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>12.8</td>
<td>10.1</td>
<td>9.0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: The Material properties of a wide band gap and conventional semiconductors at 300k [42]**

The Table 1 depicts the values of conventional semiconductors and wide band gap semiconductors. From the table we can observe that the permittivity of wide band gap semiconductor is low compared to convention semiconductor. The permittivity value of diamond is more compared to GaN and SiC. Device terminal impedance can be affected by permittivity.

Electron motilities are relatively low for GaN and SiC. The electron mobility for GaN is 900 cm\(^2\)/v-s whereas for SiC is 700 cm\(^2\)/v-s. These values are sufficient to design a transistor for high power operations. Wide band gap semiconductor has high saturation velocity and low mobility. For Al\(_x\)Ga\(_{1-x}\)N/GaN material, saturation velocity and mobility at 2DEG at heterojunction suitable for high frequency and high power device applications. The room mobility for Bulk SiC and GaN are in the ranges of 2000 cm\(^2\)/v-s and 1200 cm\(^2\)/v-s [43]. Moreover, Al\(_x\)Ga\(_{1-x}\)N/GaN structure has high charge density. Its value range is \(1 \times 10^{13} \text{cm}^2\).

Dissipated power can be measured using thermal conductivity and it is an important parameter for the device. When thermal conductivity is low it leads to degrade device operation. Generally speaking conventional semiconductors has poor thermal conductors. We can observe from the table that InP and GaN has poor thermal conductivity. On the other hand, SiC, diamond and GaN has good conductivity.
The Figure of merit is another important factor that describes the performance of the device [44]. For comparison of high frequency and a high power performance of the different materials we mostly use figure of merit. The Figure of merit combines the material properties of the device with respect to high frequency and high power applications to determine the relative strength of the materials.

2.2 Material parameters of GaN

The Table 2 below analysis the Material parameters of GaN.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>6.15g/cm</td>
</tr>
<tr>
<td>Electron mobility</td>
<td>1000cm²/Vs</td>
</tr>
<tr>
<td>Static Dielectric constant</td>
<td>8.9</td>
</tr>
<tr>
<td>Hole mobility</td>
<td>30cm²/vs</td>
</tr>
<tr>
<td>Energy Gap</td>
<td>3.39ev</td>
</tr>
<tr>
<td>Saturation velocity</td>
<td>2.5*10⁷ cm/s</td>
</tr>
<tr>
<td>Effective mass</td>
<td>0.20</td>
</tr>
<tr>
<td>Peak velocity</td>
<td>150kv/cm</td>
</tr>
<tr>
<td>Polar optical photon energy</td>
<td>91.2</td>
</tr>
<tr>
<td>Hole mass</td>
<td>0.25</td>
</tr>
<tr>
<td>Lattice constant, a</td>
<td>3.189A</td>
</tr>
<tr>
<td>Conductivity</td>
<td>1.5w/cm</td>
</tr>
<tr>
<td>Break down field</td>
<td>5*10⁶ v/m</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>2531C</td>
</tr>
</tbody>
</table>

Table 2: Material parameters of GaN [42]

2.3 GaN energy band diagram

The energy band diagram of GaN can be explained in two different structures. They are

1. Zinc blende structure
2. Wurtzite crystal structure
The above Figure 1 exhibits the energy band diagram of Zinc blende structure. The figure shows that the main energy gap is $E_g$. This energy gap is measured from valence band maxima and conduction band minima at $k$. The band diagram of a zinc blende structure has three valleys as shown in the figure. The energy gap $E_g$ is in $\Gamma$-valley whose value is $3.2\text{eV}$. Similarly, the band gap of the other valley that is $X$-valley which has the value of $4.6\text{eV}$ and $L$-valley whose value is $4.8-5.1\text{eV}$ [45].
The above Figure 2 depicts the energy band of Wurtzite structure. The structure is quite similar to the energy band diagram of zinc blende structure. \( \Gamma \)–valley has a energy value of 3.39eV, M-L valley lies in the range from 4.5eV-5.3eV, A-valley has bandgap energy from 4.7-5.5eV.

<table>
<thead>
<tr>
<th>PROPERTY/MATERIAL</th>
<th>HEXAGONAL</th>
<th>CUBIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURE</td>
<td>WURZITE</td>
<td>ZINC BLENDI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nature of Energy Gap ( E_g )</th>
<th>Direct</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Gap ( E_g ) at 0K</td>
<td>3.50eV Dingle et al 1971 Monemar 1974</td>
<td>3.30 eV Ramirez-Flores et al 1994</td>
</tr>
<tr>
<td>Energy Gap ( E_g ) at 1237K</td>
<td>2.73 eV</td>
<td>.......</td>
</tr>
<tr>
<td>Energy Gap ( E_g ) at 293-1237K</td>
<td>3.556-9.9*(10^{-4}T^2/(T+600))eV Ching-Hua Su et al, 2002</td>
<td>.......</td>
</tr>
</tbody>
</table>

Table 3: Energy bandgap properties [45]

2.4 Crystal structure of GaN

Gallium nitride is a group III nitride elements in the periodic table. GaN can adopt two crystal structures. They are

1. Zinc blende
2. Wurzite crystal structure
1. Zinc blende structure:

The structure of zinc blende is similar to that of the diamond crystal structure. The band gap $E_g$ is effected by the crystal structure. The structure has a energy gap of $3.2\text{eV}$, the ideal angle $= 109.47^\circ$ the nearest neighbor $19.5\text{nm}$.

2. Wurtzite crystal structure:

The structure resembles the structure of a hexagonal diamond. It has energy gap $E_g = 3.4\text{eV}$, ideal angle $= 109^\circ$, the nearest neighbor $= 19.5\text{nm}$. Several other compounds can take the wurtzite structure including AgI, ZnO, CdS, CdSe and other semiconductors.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ZincBlendeWurtzite.png}
\caption{GaN in the Zinc blende & wurtzite structure [45]}
\end{figure}

GaN is called as direct semiconductor. The electrons move from conduction band to valence band they release a photon which has equal in energy to that of band gap energy ($E_g$). GaN has a $3.2\text{eV}$ of band gap energy at $300\text{K}$, which is same as the wavelength of light $390\text{nm}$. The wavelength is in the violet region of the visible spectrum which is suitable for laser applications. These days we observe GaN in Blue Ray technology, which is used in the operation in the PlayStation 3 [45].

2.5 Physical properties of GaN

GaN has several remarkable properties. These physical properties make them attractive for device application in solid state [46]. GaN is a wide band gap material which has high thermal conductivity and low dielectric constants. Group III elements have high melting and high bond strengths. Further, Group III nitrides can resistant to chemical etching and
these materials can also operate in a harsh environment. Below is a Table 4 which explains about the various properties of Diamond, GaN, 4H-Sic and Si.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Diamond</th>
<th>GaN</th>
<th>4H-SiC</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expansion</td>
<td>1-2</td>
<td>5.6</td>
<td>4.2-4.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Band gap (eV)</td>
<td>5.45</td>
<td>3.45</td>
<td>3.02</td>
<td>1.12</td>
</tr>
<tr>
<td>Carrier mobility</td>
<td>2200-4500</td>
<td>1250</td>
<td>1000</td>
<td>1500</td>
</tr>
<tr>
<td>Electron mobility</td>
<td>1600-3000</td>
<td>250</td>
<td>115</td>
<td>600</td>
</tr>
<tr>
<td>Hole</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>5.7</td>
<td>9</td>
<td>9.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>2200</td>
<td>130</td>
<td>490</td>
<td>150</td>
</tr>
<tr>
<td>(W/mK)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Comparison of different wide band gap materials [46]

2.6 Material growth on the device

Material growth on the device was first developed by using MOCVD which means metal organic chemical vapor deposition. MOCVD has become the leading technology in large scale manufacturing [47]. Most of the GaN based p-n junction light emitting diodes employ other method for transition by using green and blue emission [47]. Generally Lasers and Single quantum well LED’s are using the two flow MOCVD technique. By combining the green and blue GaN LED’s we can obtain a very high intensity of full color LED and we can use this type of LEDs for displays. By using MOCVD we can understand the growth of GaN/AlInGaN materials. Therefore it has extreme importance in improving the properties of the materials at high temperatures [48] [49].

In most of the GaN device uses epitaxial layers for deposition under low pressure MOCVD over a basal plane substrate. For the growth of material ammonia and triethylgallium
materials are mostly used. Recent research on the material growth shows that to grow any material requires a minimum pressure of 76 torr and temperature of 1000°C. The carrier density of these devices will be below $10 \times 10^{15} \text{cm}^{-3}$. GaN layer can be doped as an n-type using Si as a dopant. The study on transportation properties shows that the quality of GaN epitaxial depends on the quality of the substrate. These all-situations demand for the development of bulk GaN crystals [50]. In some international research and development centers a good effort in the high pressure bulk growth of GaN is underway. The epitaxial layer has a dislocation density below the detection limit and no interface detected which make the device excellent quality.

LEO which is abbreviated as Lateral Epitaxial Overgrowth. Recently it is gaining a lot of attention in solid state electronics. This technique’s make the device much smaller than the normal GaN film which is grown on sapphire and 4H-SiC substrate. Study on threading dislocation using Lateral Epitaxial Overgrowth is in progress. By using this method we can observe a study decrease in leakage current.

Molecular Beam Epitaxy (MBE) is another technique for the growth of the epitaxial layer. The Molecular Beam Epitaxy method is similar to MOCVD in growing GaN layer. Mostly in the solid state device a smart device is preferred. By using MBE we can develop thick layers of GaN for potential applications in some power devices. Another method Hydride Vapor Phase Epitaxy (HVPE) are used in epitaxial growth. AlGaN/AlN heterostructures are developed on SiC substrate using HVPE method. In the epitaxial growth of AlN, InN and GaN fabrication of quantum dots is one interesting topic. 54 n-type GaN devices can be developed with electron density higher than $10^{19} \text{cm}^{-3}$ [51]. Similarly, the highest hole concentration in p-type is $10^{18} \text{cm}^{-3}$. This is obtained by using Mg as acceptor that creates a serious problem for the device because the ionization energy of Mg acceptor is very high that is around 160meV which is less than 1% of Mg acceptor that is activated at room temperature [52].

2.7 Substrate used for GaN

The various factors that come into play while selecting substrates such as lattice coincidence, temperature and conductivity, stability, thermal expansion coefficient and
lattice matching. The substrates used in Gallium nitrate are MgO, AlN, Si, LiAlO2, ZrB2 and SiC [53].

**Figure 4: GaN substrates comparison [53]**

Silicon is one of the most favorable substrate used to grow GaN because silicon material cost low at high temperatures, it has high thermal stability, produces big size and high quality of material. Fundamental properties of materials involved in GaN growth is shown below in Table 5
Table 5: GaN fundamental properties of materials [53]

<table>
<thead>
<tr>
<th>Material</th>
<th>Crystal Structure</th>
<th>Lattice Constant (Å)</th>
<th>Thermal Mismatch (10^-5/K)</th>
<th>Lattice Mismatch %</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>Hexagonal</td>
<td>3.18</td>
<td>5.59</td>
<td>3.17</td>
</tr>
<tr>
<td>AlN</td>
<td>Hexagonal</td>
<td>3.104</td>
<td>4.2</td>
<td>-----</td>
</tr>
<tr>
<td>Si</td>
<td>Diamond</td>
<td>5.43</td>
<td>3.59</td>
<td>-----</td>
</tr>
<tr>
<td>Sapphire</td>
<td>Hexagonal</td>
<td>4.758</td>
<td>7.5</td>
<td>8.5</td>
</tr>
</tbody>
</table>

2.8 P-type & N-type doping of GaN

At first GaN was developed using n-type doping. With the advancement in GaN technology they invented p-type doping by using low electron beam irradiation (LEEBI) and Mg treatment [54]. A scientist named Amano observed that with LEEBI and Mg treatment GaN show a low resistive value and properties of GaN started to improve. With the invention of this they soon developed a p-n GaN diode. This diode is good at the Turn on characteristics which make the device suitable for better diodes operations. Further another scientist named Nakamura et al developed a high end model of p-type doping material by thermal annealing GaN at high temperature by using nitrogen ambient [55]. To activate the dopant MOCVD uses passivation method for the growth of the material. In the growth process hydrogen is in corporate in the material and hydrogen-magnesium acceptor is formed which passivates the acceptors. By using thermal annealing at high temperature hydrogen-magnesium bond can be broken. This experiment proves that hydrogen is needed for Mg in the growth of GaN material by using MOCVD principal. In very high temperatures p-type doping becomes more complex with the activation of Mg works as dopant and on the other hand, hydrogen acts as acceptors in the CVD growth process. Energies of the magnesium dopant depends on effective mass and the dielectric constant of the materials. Group III nitrides have large effective masses and low dielectric constant which tends to high binding energy. In p-type doping, we can observe acceptor levels are
very large because of the high number of hole masses. This become a major backdrop of p-type doping. When this happens, it has two major effects

1. Low p-type doping tends to more contact resistance and
2. High n-type doping concentration leads to incomplete activation energy at the dopant end.

By increasing the p-type doping results in producing the lasers and LEDs with high power efficiency and low operating voltages. MOCVD mainly uses n-type doping which is diluted with Hydrogen in the range of 200 ppm. Mostly doping levels between 1(10^{17}) to 2(10^{19}) cm^{-3} is suitable for GaN material for the best operation.

2.9 Schottky diode

A great scientist named Schottky invented a diode and the name it as Schottky diode. Schottky diode is also called as a hot carrier diode. This device is widely used in radio frequency applications as detector or mixer. It is also used as rectifier in some power application because of its low voltage drop that tends to low power loss compared to p-n junction diodes. It has many applications in the modern scenario, but it is one of the oldest semiconductor device.

![Schottky Diode Symbol](image)

Figure 5: Schottky diode symbol [56]

The above Figure 5 represents the symbol of Schottky diode. The difference between Schottky diode and PN junction diode is as follows

1. Uses trivalent elements like aluminum metals are used. Were as p-n junction uses the trivalent impurity that is added to pure Si.
2. Threshold is low compared to the p-n junction diode usually 0.1v. On the other hand for p-n junction diode threshold voltage is higher than 0.6v
3. Thin depletion layer than p-n junction diode
4. Low junction capacitance compared to the p-n junction diode.

Consider a Schottky diode with contacts of one group that has barrier the height of 1.01ev and temperature coefficient of 20.22meV/K. Consider another group that has low barrier height approximately 0.922ev which is independent of temperature. In the first group the fermi level is charged to charge neutrality and the other is pinned by defects neutrality of the second group.

Consider distribution model that is a Non-linear transmission line. The non-linear transmission line is developed using microwave network theory. This model is very precise and it gives accurate results for the lumped element model. Use a finite difference time domain to simulate non-linear transmission line. The Finite difference time domain gives more accurate results than SPICE in simulating the Non-linear transmission line. To analyze Non-linear transmission lines, distribution model has been developed. Compared to lumped element model, distribution model provides more precise values and is used to simulate Non-linear transmission line [56].

In Schottky diode carrier transport of charges is important. Here consider reverse current temperature characteristics of GaAs Schottky diode. The temperature of the oxide interface is measured to be 250-400K at different reverse bias voltages in order to measure carrier transport. From the interface state of semiconductor model reverse current temperature can be explained based on the photon assisted electron tunneling. The process of a photon assisted tunneling process on the carrier transport is explained briefly on [57]. The electroluminescence process in phosphorus is explained using photon assisted tunneling which proved to be efficient. Undoubtedly in this process the flow of current through the barrier is carried out using the only reverse bias condition [58].

2.9.1 Schottky diode physics

Schottky diode uses semiconductor junction as in normal convention diodes. The functionality of this diode has an outcome to produce very fast switching speed and drop
in forward voltage. If semiconductor doped is p-type, only the p-type carriers play an important role in device operation. On the other side, the diode becomes free to move electrons. Fast recombination of p-type and n-type carriers occurs which results in fast conduction than the regular p-n junction diode. This in turn uses a small area in the device which suits for fast transition. Due to this advantage Schottky diode is mostly used in switching and high speed applications. Generally this device can operate in the frequency range of 200 KHz to 2 MHz Schottky diode uses smaller area so it is used mostly in RF mixers and detectors which operate in the range up to 50GHz. Generally for Schottky diode the voltage drop is between 0.15-0.45V were as for normal p-n junction the value ranges between 0.7-1.7v. The lower voltage drop indicates that the device is a high efficient device.

![Energy Band Diagram of Schottky Diode](image)

**Figure 6: Energy band diagram of the Schottky diode [58]**

The above Figure 6 shows the energy band diagram of Schottky the diode with all energy state parameters and potential parameters

$\Phi = \text{metal work function}$

$\Phi_0 = \text{Neutral level}$
\( \epsilon_l \) = permittivity of semiconductor

\( \epsilon_s \) = permittivity of the interfacial layer

\( D_{it} \) = Interface trap density

\( Q_M \) = Surface charge density of metal

\( Q_{ss} \) = Interface trap charge

\( Q_{sc} \) = Space charge density

\( \Delta \) = Potential across interfacial layer

\( \delta \) = Thickness of interfacial layer

\( \chi \) = Electron affinity of semiconductor

\( \psi_{bl} \) = Built in potential

From the Figure 6 the energy level \( q\Phi_0 \) is the neutral region. Here in neutral state, the above region are the acceptor type that is negatively charged when full, neutral when empty. As shown in the figure the region below the neutral region is the donor type that is positively charged when empty. When Fermi level coincides the neutral level charge is assumed to be zero. Further \( q\Phi_{Bno} \) is the barrier height of metal semiconductor contact.

2.10 Applications of Gallium Nitride

1. New king of Nanotube:
   - Single Crystal Nanotubes fabrication.
   - GaN nanotubes have diameter between 30-200nm.
   - Potential for mimicking ion channels.

2. GaN Laser Diode:
   - Normally emit ultraviolet radiation.
   - Indium doping allows variation in bandgap size.
   - Band gap energy range from 0.7eV-3.4eV.
   - Blue ray technology.
   - Laser printing.
3. GaN Solar cells:
   - Indium doped (InGaN).
   - Conversion of many wavelengths for energy.
   - Theoretical 70% maximum conversion rate.
     a. Multiple layers gain high efficiency.
     b. Need more layers to attain 70%.
     c. Lattice matching is not an issue.
Chapter 3: MESFET physics

MESFET encapsulate as metal semiconductor field effect transistor. The construction and terminology of MESFET is quite similar to a JFET. The only difference is Schottky junction is used instead of using p-n junction for gate. Generally Compound semiconductor technologies are used in the construction of MESFET but they lack high quality surface passivation such as SiC, InP or GaAs. These are a bit faster, but are more expensive compared to Silicon based JFETs or MESFETs. From the design perspective, MESFETs are difficult to use in digital integrated circuits because the scale goes up to large values, compared to CMOS Si based fabrication.

A great scientist named Schottky introduced the concept of Schottky barrier. The Main idea is to form a potential barrier due to the differences in work function between semiconductor contacts and metal. In 1951 William Shockley from Bell Laboratories invented the junction transistor [59]. Another scientist named Mead used the ideas of Schottky and fabricated Metal Semiconductor Field Effect Transistor (MESFET) in 1966 [59]. Metal semiconductor field effect transistor is a three terminal device. In this device electrons are the charge carriers. The charge carriers move from source to drain via a channel. The main advantages of a MESFET are

1. It has the high electron velocity inside the channel
2. Low noise device due to majority carrier transportation
3. Faster response due to small delay time and less gate capacitance
4. High switching speed

The main advantage of MESFET compared to MOSFET is MESFET has high mobility of carriers in the channel and low noise. The bulk material mobility is more than surface mobility. The main function of the depletion layer is to separate the carriers from the surface. So when the carriers are separated from the surface their mobility becomes close enough to that of bulk material [59]. As a result, large number of enhancement mode MESFET circuits cannot be fabricated because of its difficulty [60].

On the other hand, depletion mode devices provide a large transconductance and large current and the circuit contains very few transistors. So depletion mode transistors are
typically used. The MESFETs has higher transit frequency which provides particular interest towards microwave circuits [61]. The advantage of MESFET is to provide a superior microwave amplifier which limits the diode turn on condition and is tolerated [62]. Further buried channel plays a vital role in improvised noise performance as trapping. The defects are eliminated by releasing the carriers into and from surface states [63]. A block diagram and the schematic view of MESFET chip are shown below.

![Schematic view of MESFET chip](image)

**Figure 7: Schematic view of MESFET chip [63]**

![Picture of MESFET chip](image)

**Figure 8: The Picture of MESFET chip [63]**

![Block diagram of MESFET chip](image)
3.1 Construction of MESFET

The MESFET has a conducting channel placed in between drain and source terminals as shown in the Figure 9. The main function of metal contacts is to modulate the channel thickness and allowing the current or charges from the source to drain. In designing the MESFET spacing of source and drain with respect to the gate is very important. If the gate is elongated laterally indicates that MESFETS current handling ability is improved. Analog and digital MESFETS work reasonably well when then are confined to design limitations. The most complicated aspect in the design is to place the gate properly between the source and drain so that switching operation can be performed well in the respective regions. Truly speaking if the gate modulated carrier channel is narrow, the better performance of the device can be obtained.

![Figure 9: Schematic diagram of GaN MESFET [63]](image)

3.2 Study of enhancement & depletion MESFET I-V characteristics
Figure 10: (a) & (b) I-V characteristics of Depletion & Enhancement MESFETS [64]

MESFETs can be operated in depletion mode by applying a negative voltage across the gate electrode. If we apply more negative voltage at the gate the junction works as a reverse biased which results in an increase of the depletion region. If we apply more negative voltage the channel gets depleted and no current flows through the channel. The value of drain source current is low for low values of gate source voltage. Moreover, as negative voltage increases which leads to stop of the channel. So from the Figure 10 we can say that the threshold voltage is near to the lowest values of gate source voltage [64].

3.3 Types of MESFET

3.3.1 Enhancement MESFET

In an n-channel MESFET the channel is completely covered by the depletion region. The MESFET always remains in the switch off region. Enhancement MESFETs has the narrow depletion region which allows the flow of carriers. From the Figure 11 we can see that the gate is made positive by applying a positive voltage between the gate terminals and the junction in between the channel is forward biased. With the increase in channel width, the device starts conducting electricity and the current.

Figure 11: Enhancement MESFET [65]
3.3.2 Depletion MESFET

On the other hand, the n channel MESFETs the voltage at the gate terminal can be varied so depletion width can be changed. By applying a negative voltage across gate-source the flow of carrier can be stopped. In depletion MESFETs reverse biased voltage is formed between channel and gate. In n channel MESFET at a point where pinch off is achieved the MESFET behaves as a switch and the channel is completely blocked. At this stage resistance between source and drain is high [65].

![Figure 12: Depletion MESFET [65]](image)

3.4 Basic structure of MESFET device

MESFETs has two basic structures that are explained below

3.4.1 Drain and Source

In non-self-aligned structure a source and gate contact is formed before the fabrication of the gate terminal. The n or p channel region has a gate on top of it. This channel length may vary and it’s not completely dependent on the gate terminal [66].
3.4.2 Gate and Source

Separate process is used in the fabrication of the drain and source. Here we use the annealing process to fabricate the gate and source terminal using an ion implantation technique. A large gate contact is formed which can resist to higher temperatures [67].

3.5 Operation regions of MESFET

Basically MESFETS operates in three regions

1. Linear region
2. Saturation region
3. Cut-off region
Figure 15: Different regions of operation of MESFET a) Linear region b) Cutoff region c) Saturation region [68]

Figure 16: I-V characteristics of MESFET [69]
Linear region is also called as triode region. In this region the voltage and current are linearly dependent to each other. Region is active when the drain source voltage has lower values. Summing up all these things, for linear region at low values of drain source voltages, the drain current depends linearly on drain source voltages [68].

It is the region where the current remains constant with the increase in the drain source voltage. That is there is no significant increase in the value of current with the increase in $V_{ds}$. This causes the pinch off point to shift from the drain to source which results in the decrease in channel length. This leads to increase in the value of the drain source current [69].

### 3.6 Fabrication steps in MESFET

In the fabrication of GaN MESFET we use two silicon ion implantations. First one is to structure the n channel area and the second one is to form a low resistance contacts. In order to make an ohmic contact gold germanium metallization is incorporated at source and gate terminals. Using aluminum, metal pads are formed along with the Schottky gate as there are used for probing. Further using electron beam metal deposition is done. Fabrication of devices can be done by various processes such as alloying and patterning, metal deposition, annealing, ion implantation, deposition and etching, resist processing and photolithography.

**Fabrication steps:**

**Step 1:** Initially wafer should be cleaned.

**Step 2:** In the second step reactive sputtering is done for deposition silicon nitride.

**Step 3:** Resist patterning of wafer is done for channel implant. This is done by using positive resist.

**Step 4:** Ion implantation is done to fabricate the device.

**Step 5:** Shallow etching of silicon nitride for alignment purpose is done.

**Step 6:** Oxygen plasma is done to resist stripping and ashing.

**Step 7:** Resistive patterning for drain and source implants.
Step 8: Implantation of ions at source and drain regions.

Step 9: The annealing process of ion implants is done using rapid thermal annealing.

Step 10: Ohmic contacts are formed.

Step 11: Deposition of Ni/AuGe ohmic contacts using electron beam evaporation.

Step 12: Formation of ohmic contacts and Schottky gate. Si etching is done for the Schottky gate.
Figure 17: Fabrication process steps [69]
3.7 Application of MESFET device

1. MESFETS are widely used in automotive industries for high power electronic applications.

2. In telecommunication and aerospace industry MESFET has its own importance. High frequency applications such as radar, cellular and satellite communication made MESFET a potential good device for electronic component.

3. For the high data storage application we use MESFET devices.

4. MESFETS can also be used as low noise amplifiers, power amplifier, oscillators, mixers and attenuators.
Chapter 4: Scaling of device parameters

In the past three decades we have observed the exponential growth in CMOS technology. Technological innovations have enabled a constant decrease in MOSFET dimensions. In the year 1970’s the design of MOSFET’s started to decrease with the invention of the scaling factor alpha. Scaling is nothing but decreasing the size of device parameters. That is reducing the device or scaling down the device by a factor to give a relative smaller device. The below Table 6 which shows scaling rules for the device parameters.

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Generalized Scaling factor</th>
<th>Constant Field scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{ox}, X_j, W_d, L, W$</td>
<td>$1/\alpha$</td>
<td>$1/\alpha$</td>
</tr>
<tr>
<td>Doping concentrations</td>
<td>$\alpha \epsilon$</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>Power supply</td>
<td>$\epsilon/\alpha$</td>
<td>$1/\alpha$</td>
</tr>
<tr>
<td>Electric field in the device</td>
<td>$\alpha$</td>
<td>$1$</td>
</tr>
<tr>
<td>Capacitance</td>
<td>$1/\alpha$</td>
<td>$1/\alpha$</td>
</tr>
<tr>
<td>Charge Density</td>
<td>$\alpha$</td>
<td>$1$</td>
</tr>
<tr>
<td>Delay time</td>
<td>$1/\alpha$</td>
<td>$1/\alpha$</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>$\frac{\epsilon^2}{\alpha^2}$</td>
<td>$\frac{1}{\alpha^2}$</td>
</tr>
<tr>
<td>Power Density</td>
<td>$\alpha^2$</td>
<td>$1$</td>
</tr>
<tr>
<td>Circuit density</td>
<td>$\alpha^2$</td>
<td>$\alpha^2$</td>
</tr>
<tr>
<td>Chip Area</td>
<td>$\frac{1}{\alpha^2}$</td>
<td>$\frac{1}{\alpha^2}$</td>
</tr>
</tbody>
</table>
4.1 Moore’s law of scaling

The device performance of the MOSFET is widely improved by Moore’s law. Moore’s law states that the number of transistors on the integrated circuit doubles approximately every two years [70]. By using Moore’s law in the semiconductor electronics, capabilities of the device can be improved such as speed, memory capacity and efficiency.

Despite the fact that the Moore’s law has been translated diversely at the distinctive phases of the semiconductor innovation industry’s advancement, the detailing that has been acknowledged as a general agreement expresses that the quantity of segments per chip pairs like clockwork. The first supposition made by Moore, as indicated in the above Figure 18, was that the quantity of segments per chip will be multiplied at regular intervals. To be sure the initially expressed rate of advancement was kept up in the seventies, as appeared
by Moore in 1975, and proceeded to the mid-eighties. The present year and a half time of multiplying of the chip segments is adjustment in accordance with the over a wide span of time (2003) and the genuine condition of the business.

Moore’s law and its implications

![Figure 19: Cost performance of Microprocessor unit (MPU)](image)

Moore’s law had different ramifications on the microelectronics, fabricating industry and client applications by and large in the course of the most recent 30 years. As a result, expanding usefulness, cost per capacity diminishment and better execution have all been accomplished for new era of incorporated circuits.

As indicated by the international Technology Roadmap for Semiconductors (ITRS), the usefulness is characterized as the quality of bits in a measure chip or the quantity of rational transistors in a microchip unit. With the mix of more individual parts in a solitary chip the usefulness per chip expands together with the expansion in the thickness of capacities. The expansion in usefulness minimizes the postponement of information stream that happens because of the seclusion of individual capacities on independently incorporated frameworks. More usefulness additionally implies an expansion in general physical thickness of useable transistors per complete chip region. Figure 19 shows as per the ITRS,
that in both the close term (2003-2009) and the long haul (2010-2018) usefulness will be expanding by about 100% in each innovation hubs.

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4.2 Types of scaling

Scaling can be broadly classified into two types

1. Full (a constant field) scaling
2. Constant Voltage
   1. Full scaling

The dimensions of the device is scaled by the factor alpha (α) while the magnitudes of electric field inside the MOSFET remains unchanged. Due to scaling technique, charge densities are advanced by a factor alpha (α), to maintain the magnitude of the fields inside [71].

2. Constant Voltage scaling

The circuit requires certain voltage level for input and output voltages that is necessary to multiply power supply voltages. This particularly leads to constant field scaling. The dimensions of the MOSFET are reduced by alpha (α) as done in Full scaling, but the power density and power supply remains unchanged [71].
4.3 Comparison of two scaling techniques

<table>
<thead>
<tr>
<th>FULL SCALING</th>
<th>CONSTANT VOLTAGE SCALING</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ The terminal voltage and power supply voltages are scaled.</td>
<td>➢ The terminal voltage and power supply voltage are unscaled.</td>
</tr>
<tr>
<td>➢ In linear and Saturation modes drain, currents are scaled by factor alpha (α).</td>
<td>➢ In linear and Saturation modes drain, currents are multiplied by the factor alpha (α).</td>
</tr>
<tr>
<td>➢ Power dissipation is described by the factor of an alpha square (α²) in full swing.</td>
<td>➢ Power dissipation is described by the factor of alpha (α).</td>
</tr>
<tr>
<td>➢ Power density doesn’t change.</td>
<td>➢ In case of constant voltage scaling power density is increased by a factor of an alpha cube (α³).</td>
</tr>
</tbody>
</table>

However, there are two main drawbacks in the scaling

1. Sub threshold slope cannot be scaled (it can be reduced only by reducing the temperature)
2. Built in potentials cannot be scaled (it can only be changed by changing to different semiconductor) [72].

Further threshold voltage cannot be scaled too far because leakage currents will become more in the device. With the supply voltage approach, these two limitations cause deviation from the scaling theory. We have a small problem with low voltages because linear dimension are scaled very fast compared to low voltage. This can be overcome by adding a scaling factor to the electric field by using scaling rules listed in the table. Increasing the e-field means nothing but increasing the power dissipation and also the amount of doping. But this is not applicable for some low voltages because if we increase e-field it is a threat to device reliability, and therefore reliability forces us to use a low voltage supply for small devices.
Figure 20: Schematic illustration of the scaling of GaN by scaling factor alpha [72]

The above figure depicts the schematic illustration of the scaling of GaN. From the above figure, we can observe that wiring is not scaled to the same extent as gate length. The wiring does not make any gate delay. This method of approach is known as selective scaling.

The approaches to scaling relating to above are further discussed. Further by using Selective scaling we can estimate the delay of further technology generations and power densities. For a static MESFET device with high logic speed yields high performance of operation with a gate delay of 80ps. In general high speeds produce high power densities which are not suitable for some low voltage devices. High speed devices are only application for dynamic logic families. Although some low voltage devices use a low power path which helps in the initial power saving, but the power density exponentially increases in the path, for the gate length below 0.25µm [72].
Chapter 5: Theory and Equations

Figure 21: Represents the cross section view of GaN MESFET device [73]

Figure 22: a) Ion implant charge profile

b) Energy diagram of MESFET [73]

The Figure 21 represents the cross section view of GaN MESFET. Here we are going to consider the ion implantation of GaN MESFET. In the above, Figure 22 a) shows the
doping concentration of the channel, b) Depletion widths and potential profile of the device.

The figure represents the device voltages which are correlated to the fermi level at the source end. These potentials are given the signs that is positive in the downward direction and negative in the upward direction.

The impurity distribution of an ion implant device is given by Gaussian distribution function in terms of device parameters Q, σ, R_p[73].

\[ N(x,y) = \frac{Q}{\sqrt{(2\pi p t) \sqrt{(\sigma^2 + 2\pi D t)}}} \exp \left[ -\left( \frac{x-R_p}{\sqrt{2\pi(\sigma^2 + 2\pi D t)}} \right)^2 \right] - N_A \]  

Where

\[ Q = \text{Ion dose of GaN} \]
\[ R_p = \text{Implant range parameter of GaN} \]
\[ \sigma = \text{Straggle parameter of GaN} \]
\[ D = \text{Diffusion coefficient} \]
\[ t = \text{Diffusion time} \]
\[ N_A = \text{GaN Substrate concentration} \]
\[ x = \text{junction depth} \]

The substrate doping is small when compared to channel concentration and can assume as

\[ \frac{Q}{\sqrt{(2\pi p t) \sqrt{(\sigma^2 + 2\pi D t)}}} \gg N_A \]  

Here the Poisson’s equation can be solved in 2 sections

**a) MINIMUM POTENTIAL OF SURFACE TO CHANNEL:**

In the absence of free charge the Poisson’s equation is given by

\[ \frac{d^2 \phi(x)}{dx^2} = -\left( \frac{q}{\epsilon} \cdot N_A \right) \]

Where
\[ q = \text{ Electron charge} \]
\[ \epsilon = \text{GaN dielectric constant} \]
\[ \Phi = \text{Electric potential} \]

**Boundary conditions:**

\[ \Phi(0) = V_G - \Phi_A \quad \text{.................................................. (3a)} \]
\[ \frac{d\Phi(X_{DG})}{dx} = 0 \quad \text{.................................................. (3b)} \]
\[ \Phi(X_{DG}) = -\Delta + v(y) \quad \text{.................................................. (3c)} \]

Where

\[ \Phi_A = \text{Work function difference} \]
\[ \Phi(0) = \text{Surface potential} \]
\[ \Delta = \text{Depth of fermi level} \]
\[ X_{DG} = \text{Position of depletion region at the edge} \]
\[ v(y) = \text{Applied voltage} \]
\[ V_G = \text{Gate voltage} \]

At the Source end \( v(y) = 0 \)

Drain end \( v(y) = \) applied voltage \( V_{DS} \) up until pinchoff

First integration of equation (2) and substitution of (3b) gives [73]

\[ \frac{d\Phi(x)}{dx} = \frac{q*Q}{2*\epsilon} \left[ \text{erf} \left( \frac{X_{DG} - R_p}{\sqrt{2}*\sigma} \right) - \text{erf} \left( \frac{X - R_p}{\sqrt{2}*\sigma} \right) \right] + \frac{q*N_A}{\epsilon} (X - X_{DG}) \quad \text{................................. (4)} \]

Second integration of (4) and substituting of (3c) at any point in channel between drain and source is given by [73]

\[ \Phi(x) = -\left[ \frac{q*Q}{2*\epsilon} \right] (X - R_p) \left[ \text{erf} \left( \frac{X - R_p}{\sqrt{2}*\sigma} \right) - \text{erf} \left( \frac{X_{DG} - R_p}{\sqrt{2}*\sigma} \right) \right] + \frac{q*N_A}{\epsilon} (X - X_{DG})^2 - \left( \frac{q*Q*\sigma}{\epsilon*\sqrt{2}*\pi} \right) \]
\[ \left( \exp \left[ -\left( \frac{(X - R_p)^2}{2*\sigma^2} \right) \right] - \exp \left[ -\left( \frac{(X_{DG} - R_p)^2}{2*\sigma^2} \right) \right] \right) + v - \Delta \quad \text{................................. (5)} \]
Where

\[ \Delta = \text{depth of fermi level below conduction band} \]

From here we can derive the surface potential using (3a) and (5) [73]

We get

\[ V - (V_{GS} - \Phi_B) = \left( \frac{q\ast Q}{2\ast \epsilon} \right) \ast R_p \left[ \text{erf} \left( \frac{R_p}{\sqrt{2} \ast \sigma} \right) + \text{erf} \left( \frac{X_{DG} - R_p}{\sqrt{2} \ast \sigma} \right) + \left( \frac{q\ast Q\ast \sigma}{\epsilon \ast \sqrt{2} \ast \pi} \right) \exp \left[ -\left( \frac{-R_p}{2\ast \sigma} \right)^2 \right] \right] - \exp \left[ -\left( \frac{(X_{DG} - R_p)^2}{2\ast \sigma^2} \right) \right] - \frac{q\ast N_A \ast X_{DG}^2}{2\ast \epsilon} + \Delta \]

................................................................. (6)

This gives the relation between \( X_{DG} \) and voltage in the channel. If pinch off has occurred at drain \( V = V_p = V_{GS} - V_T \)

\[ X_{DG} = X_{DS} = X_p \]

................................................................. (7)

Where

\[ V_p = \text{pinch off voltage} \]
\[ \Phi_B = \text{Metal semiconductor work function} \]
\[ V_{GS} = \text{Voltage across gate to source} \]
\[ V_T = \text{Threshold voltage} \]
\[ X_p = \text{Distance from surface to channel potential} \]
\[ X_{DG} = \text{Distance from surface to edge of gate depletion region in the channel} \]
\[ X_{DS} = \text{Distance from surface to edge of substrate depletion region in the channel} \]

Then potential at the surface relation (6) at drain becomes
\[ V_p - (V_{GS} - \Phi_B) = \left( \frac{q*Q}{2*\epsilon} \right) * R_p \left[ \text{erf} \left( \frac{R_p}{\sqrt{2} \epsilon \sigma} \right) + \text{erf} \left( \frac{X_p-R_p}{\sqrt{2} \epsilon \sigma} \right) \right] + \left( \frac{q*Q*\sigma}{\epsilon*\sqrt{2} \epsilon \pi} \right) \text{exp} \left[ - \left( \frac{-R_p}{2*\sigma^2} \right)^2 \right] - \exp \left[ - \left( \frac{(X_p-R_p)^2}{2*\sigma^2} \right) \right] + \frac{q*N_A*X_p^2}{2*\epsilon} + \Delta \]  

The equation (8) gives the pinch-off voltage.

Substituting (8) from (6) to obtain [73]

\[ V - V_p = \left( \frac{q*Q}{2*\epsilon} \right) * R_p \left[ \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2} \epsilon \sigma} \right) - \text{erf} \left( \frac{X_p-R_p}{\sqrt{2} \epsilon \sigma} \right) \right] + \left( \frac{q*Q*\sigma}{\epsilon*\sqrt{2} \epsilon \pi} \right) \text{exp} \left[ - \left( \frac{(X_p-R_p)^2}{2*\sigma^2} \right) \right] - \exp \left[ - \left( \frac{(X_{DG}-R_p)^2}{2*\sigma^2} \right) \right] + \frac{q*N_A*(X_p^2-X_{DG}^2)}{2*\epsilon} \]  

(9)

b) MINIMUM CHANNEL TO GALLIUM BULK:

In this region (2) is with respect to boundary conditions

\[ \Phi(X_{DS}) = -\Delta + v(y) \]  

(10a)

\[ \frac{d(X_{DS})}{dx} = 0 \]  

(10b)

\[ \frac{d\Phi(X_W)}{dx} = 0 \]  

(10c)

\[ \Phi(X_W) = V_{BS} - V_{bi} - \Delta \]  

(10d)

Where

\[ V_{BS} = \text{Substrate to source voltage} \]

\[ V_{bi} = \text{Built in voltage of implant junction} \]

\[ X_W = \text{Distance from surface to edge of substrate depletion in the bulk} \]

Integrating of equation (2) and substituting (10b) gives the relation of electric field to (4) [73]

\[ \frac{d\Phi(x)}{dx} = - \frac{q*Q}{2*\epsilon} \left[ \text{erf} \left( \frac{X-R_p}{\sqrt{2} \epsilon \sigma} \right) - \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2} \epsilon \sigma} \right) \right] + \frac{q*N_A}{\epsilon} \left( X_{DG} - X \right) \]  

(11)

Integrating (11) and using (10a) gives the result [73]
\[ \Phi(X) = -\frac{qQ}{2\epsilon N_A} (X - R_p) \left[ \text{erf} \left( \frac{X - R_p}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{X_{DG} - R_p}{\sqrt{2}\sigma} \right) + \frac{qN_A}{2\epsilon} (X_{DG} - X)^2 + \frac{qQ}{\epsilon N_A} \frac{R_p}{p_i} \right] \]

\[
\left( \exp \left[ -\frac{(X_{DS} - R_p)^2}{2\sigma^2} \right] - \exp \left[ -\frac{(X_{DG} - R_p)^2}{2\sigma^2} \right] \right) + v - \Delta = 0 \quad \text{(12)}
\]

By substituting (10d) into (12) we get dependence of \( X_{DG} \) upon voltage [73]

\[
V_{BS} - V_{bi} = -\frac{qQ}{2\epsilon N_A} (X_W - R_p) \left[ \text{erf} \left( \frac{X_W - R_p}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{X_{DS} - R_p}{\sqrt{2}\sigma} \right) + \frac{qN_A}{2\epsilon} (X_{DS} - X_W)^2 + \frac{qQ}{\epsilon N_A} \frac{R_p}{p_i} \right] \left( \exp \left[ -\frac{(X_{DS} - R_p)^2}{2\sigma^2} \right] - \exp \left[ -\frac{(X_{DG} - R_p)^2}{2\sigma^2} \right] \right) + v \quad \text{(13)}
\]

Using condition \( E=0 \) on (10b), (10c) at both sides of the junction we get [73]

\[
\int_{X_{DS}}^{X_W} N(X) \, dx = 0 \quad \text{(14)}
\]

From (1a) and (14) we get [73]

\[
\frac{Q}{2} \left[ \text{erf} \left( \frac{X_W - R_p}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{X_{DS} - R_p}{\sqrt{2}\sigma} \right) \right] = N_A (X_W - X_{DS}) \quad \text{(15)}
\]

The condition \( X_W - R_p \gg \sigma \) will be used and so the approximation

\[
\text{erf} \left( \frac{X_W - R_p}{\sqrt{2}\sigma} \right) \approx 1 \quad \text{(16)}
\]

It is generally quite good and for the abrupt junction we have the same relation

\[
X_W - X_{DS} \approx \frac{2\epsilon}{qN_A} (V(y) + V_{bi} - V_{BS}) \quad \text{(17)}
\]

Using (16) and (17) in (15) results in [73]

\[
\text{erf} \left( \frac{X_{DS} - R_p}{\sqrt{2}\sigma} \right) \approx 1 - \frac{2\epsilon}{qN_A} \frac{2\epsilon}{\sqrt{qN_A}} (V(y) + V_{bi} - V_{BS}) \quad \text{(18)}
\]

Relationship at the drain end is given as

\[
\text{erf} \left( \frac{X_p - R_p}{\sqrt{2}\sigma} \right) \approx 1 - \frac{2\epsilon}{qN_A} \frac{2\epsilon}{\sqrt{qN_A}} (V_p + V_{bi} - V_{BS}) \quad \text{(19)}
\]

This is an expression for error function in the channel in the off condition

We also made an approximation with the terms in (5), (9), and (12), (13) [73]
\[
\text{erf}\left(\frac{X-R_p}{\sqrt{2} \cdot \sigma}\right) \text{ and } \exp\left[-\frac{(X-R_p)^2}{\sqrt{2} \cdot \sigma^2}\right] \] ....................................................... (20)

c) **DERIVING THRESHOLD VOLTAGE:**

The condition for the threshold is \( v(y) = 0 \).

Condition for threshold we have

\[
X_{DG} = X_{DS} = X_{PM} \text{ and } v(y) = V_p = 0 \] ....................................................... (21)

Where

\[
X_{PM} = \text{Maximum value } X_p .
\]

The value can be above the threshold condition (19) with \( V_p = 0 \).

\[
\Phi(0) = V_T - \Phi_B \] ................................................................. (22)

Applying \( V_G = V_T \) and equation (21) in (6) we get [73]

\[
V_T = \Phi_B - \Delta - \frac{Q \cdot q \cdot R_p}{2 \cdot \varepsilon} \left[ \text{erf}\left(\frac{X_p-R_p}{\sqrt{2} \cdot \sigma}\right) + \text{erf}\left(\frac{R_p}{\sqrt{2} \cdot \sigma}\right) \right] + \frac{Q \cdot q \cdot \sigma}{2 \cdot \varepsilon \cdot \sqrt{2} \cdot \pi} \left[ \exp\left[-\frac{(X_p-R_p)^2}{2 \cdot \sigma^2}\right] - \exp\left[-\left(\frac{R_p}{\sqrt{2} \cdot \sigma}\right)^2\right] \right] \] ................................................................. (23)

Now substituting (19) and (20) into (23) we get \( V_T \) as [73]

\[
V_T = \Phi_B - \Delta - \frac{Q \cdot q \cdot R_p}{2 \cdot \varepsilon} \left[ \text{erf}\left(\frac{R_p}{\sqrt{2} \cdot \sigma}\right) + 1 - \frac{2 \cdot N_A}{Q} \sqrt{\frac{2 \cdot \varepsilon}{q \cdot N_A}} \left( V_{bi} - V_{BS} \right) \right] - \frac{Q \cdot q \cdot \sigma}{\varepsilon \cdot \sqrt{2} \cdot \pi} \left[ \exp\left[-\frac{R_p^2}{2 \cdot \sigma^2}\right] \right] \] ................................................................. (24)

\[d) \text{ **CHARACTERISTICS OF MESFET DEVICE:**} \]

The I-V characteristics are derived in general from field effect transistor (6),(7) [73]

\[
I_{DS} = q \cdot u \cdot \frac{Z}{L} \int_0^{V_{DS}} \text{Q}_n(v)dv \] ................................................................. (25)

Where

\[
q = \text{Electron charge} \\
u = \text{Electron Mobility}
\]
\[ Z = \text{Device width} \]
\[ L = \text{Device length} \]
\[ Q_n = \text{Mobile channel charge} \]

1) CHANNEL CHARGE:

The channel charge is written as

\[ Q_n = \int_{X_{DG}}^{X_{DS}} N(x) dx \] ................................. (26)

Where

\[ N(x) = \text{Concentration of implant impurity ions} \]

Here we neglect the background concentration in the implant region using approximation (1) so that equation (26) becomes as follows [73]

\[ Q_n = \frac{Q}{2} [\text{erf} \left( \frac{X_{DS}-R_p}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2}\sigma} \right)] \] ................................. (27)

In order to get \( Q_n \) we want above two error function terms in (27).

\[ V - V_p = \frac{q^*Q^*R_p}{2\epsilon} \left[ \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2}\sigma} \right) - 1 + a_p \right] + \frac{q^*Q^*\sigma}{\epsilon^*2^*p_l} \left[ \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2}\sigma} \right)^2 - (1 - a_p)^2 \right] \] ... (28)

Where

\[ a_p = \text{dimensionless quantity} \]

\[ a_p = \frac{2^*N_A}{Q} \cdot \frac{2^*\epsilon}{q^*N_A} (V_{bi} - V_{BS} + V_p) \] ................................. (29)

According to (1b) the term \( \left( \frac{q^*N_A}{2\epsilon} \right)((X_p^2 - X_{DG}^2)) \) has been terminated from (9) in getting (27). The above equation is quadratic equation in \( \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2}\sigma} \right) \) whose solution is [73]

\[ \text{erf} \left( \frac{X_{DG}-R_p}{\sqrt{2}\sigma} \right) = -\frac{R_p}{2\sigma} \sqrt{\frac{p_l}{2}} + \left\{ \frac{R_p}{2\sigma} \sqrt{\frac{p_l}{2}} \right\}^2 + \frac{R_p}{\sigma} \sqrt{\frac{p_l}{2}} (1 - a_p) + (1 - a_p)^2 + \frac{\sqrt{2^*p_l^*e}}{q^*Q^*\sigma} (V - V_p)^{\frac{1}{2}} \] ................................. (30)
Substituting (18) and (30) into (27) yields [73]

\[ Q_n = \frac{Q}{2} \{ 1 + \alpha - (a^2 + \frac{V-V_p}{V_1})^{\frac{1}{2}} - [(\alpha + 1 - a_p)^2 + \frac{V-V_p}{V_2}]^{\frac{1}{2}} \} \] ........................ (31)

Where

\[ \alpha = \frac{R_p}{2*\sigma} \sqrt{\frac{pi}{2}} \] ........................ (32a)

\[ V_1 = \frac{q*Q^2}{8*N_A*\epsilon} \] ........................ (32b)

\[ V_2 = \frac{q*Q*\sigma}{\sqrt{2*pi*\epsilon}} \] ........................ (32c)

2) CHANNEL CURRENT:

It is obtained by integrating (31) in (25) we get [73]

\[ I_{DS} = \frac{q*Q*U*Z}{2*L} [V_{DS}(1 + \alpha) - 2 \frac{q*Q*N_A^2}{3*Q*\epsilon} \left( \left( \frac{2*\epsilon}{q*N_A} \right) (V_{bi} - V_{BS} + V_{DS}) \right)^{\frac{3}{2}} + 2 \frac{q*Q*N_A^2}{3*Q*\epsilon} \left( \left( \frac{2*\epsilon}{q*N_A} \right) (V_{bi} - V_{BS}) \right)^{\frac{3}{2}} - 2 \frac{Q*\sigma}{3*\epsilon} \sqrt{\frac{2}{pi}} [\alpha^2 - 2 * \alpha c_1 + c_1^2 + R (V_{DS} - V_{GS} + \Phi_Bn - \Delta)^{\frac{3}{2}} + \frac{q*Q*\sigma}{3*\epsilon} \sqrt{\frac{2}{pi}} [\alpha^2 - 2 * \alpha c_1 + c_1^2 + R (-V_{GS} + \Phi_Bn - \Delta)^{\frac{3}{2}}] \] ........................ (33)

Where

\[ \alpha = \frac{R_p}{2*\sigma} \sqrt{\frac{pi}{2}} \] ........................ (33a)

\[ R = \frac{\epsilon \sqrt{2*pi}}{q*Q*\sigma} \] ........................ (33b)

\[ C_1 = \text{erf} \left( \frac{R_p}{\sigma \sqrt{2}} \right) \] ........................ (33c)

\[ C_2 = V - V_{GS} + \Phi_B - \Delta \] ........................ (33d)

d) INTERNAL GATE CAPACITANCE:

As shown in the figure the space charge region has three regions that is section I, II and III along with the respective charges \( Q_1, Q_2, Q_3 \).
Region I: In this section gate changes linearly with distance from Source to Drain.

Compared to region I, region II and III are small quarter areas.

Figure 23: Space charge distribution [73]

If we consider impedances, at higher impedance state gate bias is \( V_p \) and in lower impedance case the gate bias is zero. In addition to contact resistances the device circuit consists of some intrinsic parameters. These intrinsic parameters include resistance, capacitance, drain source, gate drain and gate source.

The charge

\[
Q_1 = q * Z * L * \int_{0}^{X_{SG}} N(x) dx + \left[ \frac{q * Z * L}{X_{DG} - X_{SG}} \right]^{X_{DG}}_{X_{DS}} N(x) (X_{DG} - X) dx \] ……………… (34a)

\[
Q_1 = q * Z * L * \int_{0}^{X_{DG}} N(x) dx - \left[ \frac{q * Z * L}{X_{DG} - X_{SG}} \right]^{X_{DG}}_{X_{DS}} N(x) (X - X_{DG}) dx \] ……………… (34b)

Substituting (1) in (34a) and (34b) we get [73]

\[
Q_1 = \frac{q * Q * Z + L}{2} \left[ (MR + A_1) \frac{1}{N^Z} + A_2 + \frac{1}{N^Z (MN + A_1) \frac{1}{N^Z - R^Z}} - \frac{1}{N^Z (MR + A_1) \frac{1}{N^Z - R^Z}} \right] - \frac{1}{Q} \left( \frac{2 * N_B + e \epsilon_s}{q} \right)^{\frac{1}{2}} \left( V_D - V_S \right) \frac{1}{N^Z - R^Z} \] \] ………………………………………………………………………………………… (35a)

\[
Q_1 = \frac{q * Q * Z + L}{2} \left[ (MN + A_1) \frac{1}{N^Z} + A_2 - \frac{1}{N^Z (MN + A_1) \frac{1}{N^Z - R^Z}} + \frac{1}{N^Z (MN + A_1) \frac{1}{N^Z - R^Z}} \right] - \frac{1}{Q} \left( \frac{2 * N_B + e \epsilon_s}{q} \right)^{\frac{1}{2}} \left( V_D - V_S \right) \frac{1}{N^Z - R^Z} \] \] ………………………………………………………………………………………… (35b)

Where
\[ N = V_{bi} - V_G - V_D \]
\[ R = V_{bi} - V_G + V_s \]
\[ M = \frac{4 + \alpha + \epsilon}{q \cdot Q \cdot R_p} \]
\[ A_1 = \alpha^2 + A_3 \]
\[ \alpha = \frac{R_p}{2 \sqrt{(\sigma^2 + 2Dt)}} \cdot \sqrt{\frac{p_i}{2}} \]
\[ A_2 = \text{erf}\left(\frac{R_p}{2 \sqrt{\sigma^2 + 2Dt}}\right) - \alpha \]
\[ A_3 = 1 - \exp\left(-\left(\frac{R_p}{\sqrt{2(\sigma^2 + 2Dt)}}\right)^2\right) - 2 \alpha \cdot \text{erf}\left(\frac{R_p}{\sqrt{2(\sigma^2 + 2Dt)}}\right) \]

The charge \( Q_2 \) and \( Q_3 \) in section II and III can be expressed as:

\[ Q_2 = \frac{p_i}{2} \cdot \epsilon \cdot Z \cdot (V_{bi} - V_G + V_s) \] ................................. (36)
\[ Q_3 = \frac{p_i}{2} \cdot \epsilon \cdot Z \cdot (V_{bi} - V_G + V_D) \] ................................. (37)

Summing up internal capacitance at gate source give us

\[ C_{GS} = C_{GS1} + C_{GS2} + C_{GS3} \]
\[ C_{GS} = \left(\frac{dQ_T}{dV_s} \cdot \frac{1}{V_G}\right) = \text{constant} \]

\[ C_{GS} = \frac{q + Q+Z+L}{2} \left[ \frac{M}{2(MR + A_1)} \right] + \sqrt{\frac{N}{(\sqrt{N} - \sqrt{R})^2}} \left( \frac{(MN + A_1)^{\frac{1}{2}}}{\sqrt{R}} - \frac{M(\sqrt{N} - \sqrt{R})}{(MR + A_1)^{\frac{1}{2}}} - \frac{(MR + A_1)^{\frac{1}{2}}}{\sqrt{R}} - \frac{1}{Q} \right) \cdot \sqrt{\frac{2N_B}{q}} \]
\[ + \frac{2(\sqrt{N} - \sqrt{R})}{\sqrt{R}} + \frac{V_{DS}}{\sqrt{R}} \] ................................. (38)

Similarly internal gate drain capacitance
\[ C_{GD} = \frac{qQ+ZL}{2} \left[ \frac{M}{2(MN+A_1)^2} + \frac{\sqrt{R}}{(\sqrt{N}-\sqrt{R})^2} \right] + \frac{1}{Q} \left[ \frac{M(N-A_1)^{\frac{1}{2}}}{\sqrt{MN}} \right] - \frac{1}{Q} \left[ \frac{(MN+A_1)^{\frac{1}{2}}}{\sqrt{MN}} \right] - \frac{1}{Q} \sqrt{\frac{2+N_B+\epsilon}{q}} + \frac{1}{2} \epsilon * Z \]  

\[ \left( \frac{2(\sqrt{N}-\sqrt{R})}{\sqrt{R}} - \frac{V_{DS}}{\sqrt{RN}} \right) \right] + \frac{p_i}{2} * \epsilon * Z \]  

\[ \frac{2}{\sqrt{2}} \left( \frac{\sigma^2+2+D+T}{\epsilon} \right) \]  

\( R_{DS} = \frac{q+u+ZQ}{2+L} \left[ \left( 1 + \alpha \right) - (a_p^2 - \frac{V_p}{V_1})^\frac{1}{2} - \left( (\alpha + 1 - a_p)^2 - \frac{V_p}{V_2} \right)^\frac{1}{2} \right] + \frac{p_i}{2} * u * \]  

\( \left[ \frac{2+\epsilon q+V_b+Q}{\sqrt{2+pi(\sigma^2+2+D+T)}} \right]^{-1} \)  

\[ \frac{qQ^2}{8N_A+\epsilon} \]  

\[ \frac{qQ+\sqrt{\sigma^2+2+D+T}}{\sqrt{2+pi+\epsilon}} \]  

\[ \frac{2+N_A}{Q} \sqrt{\frac{2+\epsilon}{q+N_A}} (V_b - V_{BS} + V_p) \]  

\[ g_m = \frac{dI_{DS}}{dV_{GS}} \]  

\[ \frac{q+u+ZQ}{4+L} \left[ \frac{1}{V_1 a_p} + \frac{1}{V_2 (\alpha+1-a_p)} \right] (V_{GS} - V_T) \]  

Where

\[ q = \text{Electronic charge} \]
Electron mobility
channel width
channel Length
Ion implant dose
Gate to Source Voltage
Threshold voltage
\[ V_1 = \frac{qQ^2}{8\times N_A \times \varepsilon} \]
\[ V_2 = \frac{qQ\sqrt{\sigma^2 + 2D\varepsilon}}{\sqrt{2\times \pi \varepsilon}} \]
\[ a_p = \frac{2\times N_A}{Q} \sqrt{\frac{2\times \varepsilon}{q\times N_A} (V_{b_i} - V_{BS} + V_p)} \]

**g) CUT-OFF FREQUENCY:**

Cut-off frequency is obtained by using equation (42), (38) [73]

\[ f_T = \frac{g_m}{2\times p_i \times C_{gs}} \]  \hspace{1cm} \text{(43)}

Where

\[ g_m = \text{Transconductance} \]
\[ C_{gs} = \text{Gate to Source Capacitance} \]

**h) TIME DELAY:**

The time delay is obtained by adding equation (38) and (39) and multiplying it with equation (40) [73]

We get

\[ T_d = R_{ds} (C_{gs} + C_{gd}) \]  \hspace{1cm} \text{(44)}
Where

\[
\begin{align*}
R_{ds} &= \text{Resistance from drain to source} \\
C_{gs} &= \text{Capacitance from gate to source} \\
C_{gd} &= \text{Capacitance from gate to drain}
\end{align*}
\]

i) **POWER:**

Power is obtained by multiplying current and voltage from drain to source, i.e. multiplying equation (33) with \(V_{DS}\) [73]

\[
P = I_{DS} \times V_{DS} \]

(45)
Chapter 6: Results and Discussions

A physics based model has been developed to study the effect of scaling down on drain current, threshold voltage, cut-off frequency, time delay and power. The analytical model has been computed by using MATLAB and required results are obtained that are shown below.

![Image of Figure 24]

**Figure 24: Drain to source current (I_{ds}) vs drain to source voltage (V_{ds})**

The above Figure 24 exhibits the plot of drain to source current (I_{ds}) versus drain to source voltage (V_{ds}) for different gate to source voltage (V_{gs}) of 0V,-2V,-4V with substrate concentration (N_d) of 1x10^{12} cm^{-3} ,doping concentration of channel (N_d) of 1.38x10^{17} cm^{-3}, ion dose (Q) of 5x10^{12} cm^{-2}, channel length (L) of 0.5x10^{-4} cm and pinch-off voltage (V_p) of 1.45V. The fabrication parameters were generated from SRIM.
namely straggle parameter (σ) = 7.39x10^{-8} cm and implant range parameter (R_p) = 1.767x10^{-8} cm. The drain current in the I-V characteristics shows clearly the linear and non-linear increase of the current. The drain current obeys the ideal I-V characteristics of MESFET. The I-V characteristics plot has been generated by using the equation (33).

**Figure 25: Variation of drain to source current (I_{ds}) vs Scaling factor (alpha)**

The above Figure 25 shows the plot of drain to source current (I_{ds}) versus scaling factor (alpha) for different drain to source voltages (V_{ds}) = 5V, 10V, 15V with constant channel doping concentration (N_d) = 1.38x10^{17} cm^{-3}, substrate concentration (N_a) = 1x10^{12} cm^{-3}, device width (Z) = 5.0x10^{-4} cm, channel length (L) = 0.5x10^{-4} cm. The fabrication parameters were generated from SRIM namely straggle parameter (σ) = 7.39x10^{-8} cm and implant range parameter (R_p) = 1.767x10^{-8} cm. The drain to source current (I_{ds}) values are
obtained for ideal case 0.6, 1.2, 1.8 Amps. When the scaling factor alpha = 2 the drain to source current \( I_{ds} \) values are scaled down to 0.3, 0.6, 0.9 Amps. This indicates when the scaling factor (alpha) is applied the channel current is also scaled down due to the other parameters scaled down by half and the currents falls rapidly, tending to saturation point. Further for remaining values of alpha greater than 3 the current values are further reduced. The I-V characteristics has been generated using the equation (33).

The appendix includes the MAT Lab code used for this simulation

![Figure 1](image)

**Figure 26: Threshold voltage \( V_T \) vs Scaling factor (alpha)**

Matlab code as shown in the appendix was utilized in order to obtain the graphs a shown in the Figure 26. Figure 26 shows the plot of threshold voltage \( V_T \) versus scaling factor and (alpha) for separate values of substrate concentration \( (N_a) = \)
2x10^{12} \text{cm}^{-3}, 1x10^{14} \text{cm}^{-3}, 4x10^{14} \text{cm}^{-3} \text{ with device width (Z) } = 500 \times 10^{-4} \text{cm, channel length (L) } = 0.5 \times 10^{-4} \text{cm. The fabrication parameters were generated from SRIM namely straggle parameter (} \sigma \text{) } = 739 \times 10^{-8} \text{cm and implant range parameter (} R_p \text{) } = 1767 \times 10^{-8} \text{cm. Threshold voltages (} V_T \text{) are obtained as } -1.48 \text{V, } -1.36 \text{V, } -1.15 \text{V for non-scaled devices. When scaling factor alpha } = 2 \text{ the threshold voltages (} V_T \text{) are reduced to half and threshold scaling values becomes } -0.74 \text{V, } -0.68 \text{V, } -0.57 \text{V respectively. It is observed that Threshold voltage (} V_T \text{) changes sharply for higher substrate concentration in the enhancement device when scaling factor (alpha) varies from 1 to 2. However, for larger scaling factor (alpha) the change in threshold voltage (} V_T \text{) is very small or meeting to saturation value. The threshold voltage (} V_T \text{) has plotted by using the equation (24a). The appendix includes the MAT Lab code used for this simulation.}

![Figure 1](image)

**Figure 27:** Cut-off frequency (\( F_T \)) vs Channel Length (L)
The Figure 27 exhibits the plot for cut-off frequency ($F_t$) versus channel length (L) and are scaled down by scaling factor (alpha) =1, 2, 3 for channel doping concentration $N_d$ =1.38x10$^{17}$ cm$^{-3}$, substrate concentration $N_a$ =1x10$^{12}$ cm$^{-3}$, device width $Z$ = 500x10$^{-4}$ cm. The fabrication parameters were generated from SRIM namely straggle parameter ($\sigma$) =739x10$^{-8}$ cm and implant range parameter ($R_p$) =1767x10$^{-8}$ cm. The cut-off frequency ($F_t$) changes sharply as the channel length (L) varies from 1 to 2 $\mu$m. For channel length (L) greater than 2 $\mu$m the frequency tends to be independent of channel length (L). Large scaling factor leads to saturate the cut-off frequency ($F_t$). The cut-off frequency ($F_t$) has been plotted using the equation (43).

The appendix includes the MAT Lab code used for this simulation.
The Figure 28 exhibits a plot for time delay \( (T_d) \) versus channel length \( (L) \) scaled down by scaling factor \( \alpha = 1, 2, 3 \) with channel doping concentration \( (N_d) = 1 \times 10^{17}\text{cm}^{-3} \), substrate concentration \( (N_a) = 1 \times 10^{12}\text{cm}^{-3} \), device width \( Z = 2 \times 10^{-4}\text{cm} \). The fabrication parameters were generated from SRIM namely straggle parameter \( (\sigma) = 739 \times 10^{-8}\text{cm} \) and implant range parameter \( (R_p) = 1767 \times 10^{-8}\text{cm} \). When scaling is applied on the channel length the time delay reduces for scaled channel length. The value of time delay decreases significantly for different values of channel length. The time delay \( (T_d) \) has plotted using the equation (44).

![Figure 1](image)

**Figure 29: Power \( (P_w) \) vs drain to source voltage \( (V_{ds}) \)**

The Figure 29 exhibits the plot for power \( (P_w) \) versus drain to source voltage \( (V_{ds}) \) for various values of scaling factor applied for doping concentration \( (N_d) = 1.38 \times 10^{17}\text{cm}^{-3} \),
substrate concentration \( (N_a) = 1 \times 10^{12} \text{cm}^{-3} \), device width \( (Z) = 500 \times 10^{-4} \text{cm} \), channel length \( (L) = 0.5 \times 10^{-4} \text{cm} \). The fabrication parameters were generated from SRIM namely straggle parameter \( (\sigma) = 739 \times 10^{-8} \text{cm} \) and implant range parameter \( (R_p) = 1767 \times 10^{-8} \text{cm} \).

As the scaling factor is applied to the electrical parameters the drain to source voltages are scaled down. It is evident in the plot, by observing the less power obtained by the scaled device. It is clear that the scaled device power dissipation is much less than the unscaled device. The power \( (P_w) \) graph has plotted by using the equation (45).
Conclusion

An analytical model has been developed to study the scaling effect of different electrical parameters of GaN base MESFET. The device dimensions, doping concentration and fabrication parameters have been scaled to evaluate the scaling effect on the drain current, threshold voltage, cutoff frequency, time delay and dc output power. The scaling results in the cut-off frequency, time delay and dc output power showed an interesting results how to establish the device for high power RF applications. This research work on GaN MESFET devices begins to look very promising research in future scope. The results show the scaling effects on the device parameters having positive impact on device fabrication. It is also anticipated that the scaling results reaches to the saturated point beyond some extent of scaling the device.
References


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[18] Emerging Gallium Nitride Based Devices S.N Mohammad and Hadis Morkoc, fellow, IEEE.


APPENDIX I

SYMBOLS AND NOTATIONS USED:

q: Electronic charge

\( \varepsilon \): Permittivity

L: Channel length

W: Width of the device

\( \mu \): Mobility

\( \Delta X_j \): Change in junction depth

\( V_{bi} \): Built in voltage

\( V_{s} \): Channel potential at the surface end

\( V_{D} \): Channel potential at the drain end

\( V_{G} \): Gate potential

\( V_{GS} \): Gate to Source voltage

\( V_{DS} \): Drain to Source voltage

\( V_{GD} \): Gate to Drain voltage

\( V_{th} \): Threshold voltage

\( V_{p} \): Pinchoff voltage

\( V_{BS} \): Substrate to source voltage

\( Q_T \): Total space charge in the depletion region

\( P_T \): Total charge density in the depletion region

\( C_{gs} \): Internal gate source capacitance below pinchoff

\( C_{gd} \): Internal gate drain capacitance below pinchoff
\( R_{ds} \): Internal drain to source resistance

\( f_T \): Cutoff frequency

\( N_B \): Substrate concentration

\( N_s \): Average concentration

Q: Ion implant dose

\( R_p \): Ion implant projected range

D: Diffusion coefficient of ion implant

t: Annealing time

\( T_A \): Annealing temperature

\( \sigma \): Ion implant Straggle parameter

\( \alpha \): Scaling parameter
APPENDIX II

Variation of Drain to Source voltage versus Drain to source current

Clc;

clear all;

q = 1.6e-19;

Z = 500e-4;

Q = 5e12;

sigma = 739e-8;

u = 300;

L = 0.5e-4;

D = 0.74e-15;

t=1273;

eo = 9.7;

es = 8.858e-14;

Es = eo*es;

T = 300;

Nd = 1.38e18;

Nc = 4.3e14*T^1.5;

Nv = 8.9e15*T^1.5;

Eg = 3.40;

a = 0.3e-4;

k = 1.38e-23;

Vt = (k*T)/q;
Vbs= -6;
Na = 1e12;
pib = 2;
delta = 0.1;
alpha = 1.5;
Rp=1767e-8;
Vp = (q*Q*a^2)/(2*Es*sqrt(sigma^2+(2*D*t))*(sqrt(2*pi)));
Ni = sqrt(Nc*Nv)*(exp(-Eg/(2*Vt)));
Vbi = Vt*log(Nd/Ni);
V=10;
Vds=0:1:10;
for Vgs=-4;
R=(Es*sqrt(2*pi))/(q*Q*sigma);
C1=erf(Rp/(sigma*sqrt(2)));
C2=(V-Vgs+pib-delta);
a1 = (q*Q*u*Z)/(2*L);
a2 = (Vds.*(1+alpha));
a3 = (2*q*Na^2)/(3*Q*Es);
a4 = (2*Es)/(q*Na);
a5 = (Vbi-Vbs+Vds);
a6 = (Vbi-Vbs);
a7 = (q*Q*sigma)/(3*Es);
a8 = sqrt(2/pi);
a9 = alpha.^2-(2.*alpha.*C1)+(C1.^2);

a10 = R*(Vds-Vgs+pib-delta);

a11 = R*(-Vgs+pib-delta);

Ids=a1.*(a2-
(a3.*(a4.*a5).^1.5)+(a3.*(a4.*a6).^1.5)(a7.*a8.*(a9+a10).^1.5)+(a7.*a8.*(a9+a11).^1.5)
)

plot (Vds,Ids,'r');

hold on;

end;

for Vgs=-2;

R=(Es*sqrt(2*pi))/(q*Q*sigma);

C1=erf(Rp/(sigma*sqrt(2)));

C2=(V-Vgs+pib-delta);

a1 = (q*Q*u*Z)/(2*L);

a2 = (Vds.*(1+alpha));

a3 = (2*q*Na^2)/(3*Q*Es);

a4 = (2*Es)/(q*Na);

a5 = (Vbi-Vbs+Vds);

a6 = (Vbi-Vbs);

a7 = (q*Q*sigma)/(3*Es);

a8 = sqrt(2/pi);

a9 = alpha.^2-(2.*alpha.*C1)+(C1.^2);

a10 = R*(Vds-Vgs+pib-delta);
a11 = R*(-Vgs+pib-delta);

Ids1=a1.*(a2-
(a3.*(a4.*a5).^1.5)+(a3.*(a4.*a6).^1.5)(a7.*a8.*(a9+a10).^1.5)+(a7.*a8.*(a9+a11).^1.5)
)

plot(Vds,Ids1,'b');

hold on;

end;

for Vgs=0;

R=(Es*sqrt(2*pi))/(q*Q*sigma);

C1=erf(Rp/(sigma*sqrt(2)));

C2=(V-Vgs+pib-delta);

a1 = (q*Q*u*Z)/(2*L);

a2 = (Vds.*(1+alpha));

a3 = (2*q*Na^2)/(3*Q*Es);

a4 = (2*Es)/(q*Na);

a5 = (Vbi-Vbs+Vds);

a6 = (Vbi-Vbs);

a7 = (q*Q*sigma)/(3*Es);

a8 = sqrt(2/pi);

a9 = alpha.^2-(2.*alpha.*C1)+(C1.^2);

a10 = R*(Vds-Vgs+pib-delta)

a11 = R*(-Vgs+pib-delta)
Ids2=a1.*(a2-(a3.*(a4.*a5).^1.5)+(a3.*(a4.*a6).^1.5)(a7.*a8.*(a9+a10).^1.5)+(a7.*a8.*(a9+a11).^1.5))
plot(Vds,Ids2,'g');
hold on;
end;
xlabel('Drain to Source Voltage Vds, (Volts)');
ylabel('Drain to Source Current Ids, (Amps)');
title('Variation of Drain to Source current Vs Drain to Source Voltage');
legend('Vgs = -4V','Vgs = -2V','Vgs = 0V');

Variation of scaling factor versus drain to source current

clear all;
cle;
alpha = 1:0.1:8;
q = 1.6e-19;
Q = 5e12;
u = 300;
Z = 500e-4./alpha;
L = 0.5e-4./alpha;
Na = 1e12.*alpha;
Nd = 1.38e18.*alpha;
Es = 9.7*8.854e-14;
T=300;
\[ N_v = (8.9e15 \times T^{1.5}) \times \alpha; \]
\[ N_c = (4.3e14 \times T^{1.5}) \times \alpha; \]
\[ k = 1.38e^{-23}; \]
\[ V_t = \frac{k \times T}{q}; \]
\[ N_i = (\sqrt{N_c \times N_v} \times (\exp(-\frac{E_s}{2 \times V_t})) \times \alpha; \]
\[ V_{bi} = \frac{V_t \times \log(N_d / N_i)}{\alpha}; \]
\[ V_{bs} = -6./\alpha; \]
\[ V_{gs} = -4./\alpha; \]
\[ \sigma = 739e^{-8}; \]
\[ R_p = 1767e^{-8}; \]
\[ \pi_b = 2; \]
\[ \delta = 0.1; \]
\[ \alpha_1 = \frac{R_p}{2 \times \sigma} \times \sqrt{\pi/2}; \]
\[ V_{ds} = (5)./\alpha; \]
\[ R = \frac{E_s \times \sqrt{2 \pi}}{(q \times \sigma)}; \]
\[ c_1 = \text{erf}\left(\frac{R_p}{(\sigma \times \sqrt{2})}\right); \]
\[ a_1 = \frac{q \times \sigma}{(2 \times L)}; \]
\[ a_0 = V_{ds} \times (1 + \alpha_1); \]
\[ a_2 = -\frac{(2 \times q \times \sigma^2)}{(3 \times Q \times E_s) \times ((2 \times E_s)/(q \times N_a) \times (V_{bi} - V_{bs} + V_{ds}))^{1.5}}; \]
\[ a_3 = \frac{(2 \times q \times \sigma^2)}{(3 \times Q \times E_s) \times ((2 \times E_s)/(q \times N_a) \times (V_{bi} - V_{bs}))^{1.5}}; \]
\[ a_4 = -\left((q \times \sigma^{1.5}) \times (\sqrt{2/\pi}) \times (\alpha_1^{0.5} - 2 \times \alpha_1 \times c_1 + c_1^{1.5} + R \times (V_{ds} - V_{gs} + \pi_b - \delta))^{1.5}\right); \]
a5 = ((q*Q*sigma).*(sqrt(2/pi)).*(alpha1.^2-(2.*alpha1.*c1)+c1^2+R*(-Vgs+pibn-delta)).^1.5);
Ids = (a1.*(a0+a2+a3+a4+a5))
plot(alpha,Ids,'r');
hold on;
Vds = (10)./alpha;
R = (Es*sqrt(2*pi))/(q*Q*sigma);
c1 = erf(Rp/(sigma*sqrt(2)));
a1 = (q*Q*u.*Z)/(2.*L);
a0 = Vds.*(1+alpha1);
a2 = -(2*q.*Na.^2)./(3*Q*Es).*((2*Es)./(q.*Na).*(Vbi-Vbs+Vds)).^1.5;
a3 = (2*q.*Na.^2)./(3*Q*Es).*((2*Es)./(q.*Na).*(Vbi-Vbs)).^1.5;
a4 = -((q*Q*sigma).*(sqrt(2/pi)).*(alpha1.^2-(2.*alpha1.*c1)+c1^2+R*(Vds-Vgs+pibn-delta)).^1.5);
a5= ((q*Q*sigma).*(sqrt(2/pi)).*(alpha1.^2-(2.*alpha1.*c1)+c1^2+R*(-Vgs+pibn-delta)).^1.5);
Ids1 = (a1.*(a0+a2+a3+a4+a5))
plot(alpha,Ids1,'b');
hold on;
Vds = (15)./alpha;
R = (Es*sqrt(2*pi))/(q*Q*sigma);
c1 = erf(Rp/(sigma*sqrt(2)));
a1 = (q*Q*u.*Z)/(2.*L);
a0 = Vds.*(1+alpha1);

a2 = -(2*q.*Na.^2)./(3*Q*Es).*((2*Es)./(q.*Na).*((Vbi-Vbs+Vds)).^1.5;

a3 = (2*q.*Na.^2)./(3*Q*Es).*((2*Es)./(q.*Na).*((Vbi-Vbs)).^1.5;

a4 = -(q*Q*sigma).*(sqrt(2/pi)).*(alpha1.^2-(2.*alpha1.*c1)+c1^2+R*(Vds-Vgs+pibn-delta)).^1.5);

a5=((q*Q*sigma).*(sqrt(2/pi)).*(alpha1.^2-(2.*alpha1.*c1)+c1^2+R*(-Vgs+pibn-delta)).^1.5);

Ids2 = (a1.*(a0+a2+a3+a4+a5))

plot(alpha,Ids2,'g');

xlabel('Scaling factor (alpha)');
ylabel('Drain to Source Current Ids, (Amps)');
title('Variation of Drain to Source current Vs Scaling factor');
legend('Vds=5','Vds=10','Vds=15');

Variation of scaling factor versus threshold voltage

clear all;
clc;

alpha = 1:0.1:3;
q = 1.6e-19;
Q = 2e12;
u = 300;
Z = 500e-4./alpha;
L = 0.5e-4./alpha;
Nd = 1.38e18.*alpha;
Es = 9.7*8.854e-14;
T=300;
Nv = (8.9e15*T^1.5).*alpha;
Nc = (4.3e14*T^1.5).*alpha;
k = 1.38e-23;
Vt = ((k*T)/q)./alpha;
Ni = (sqrt(Nc.*Nv).*exp(-Es./(2.*Vt))).*alpha;
Vbi=1.45./alpha;
Vbs = -10./alpha;
Vgs = -2./alpha;
Rp=1767e-8;
sigma=739e-8;
D=0.74e-15;
t=1273;
pibn = 2;
delta = 0.1;
Vds = 4./alpha;
for Na =2e12;
 a1 = (q*Q*Rp)/(2*Es);
 a2 = erf(Rp/(sqrt(2*sqrt(sigma^2+(2*D*t)))));
 a3 = 1-((2.*Na/Q).*sqrt((2.*Es./(q.*Na)).*(Vbi-Vbs)));
 a4 = (q*Q*sqrt(sigma^2+(2*D*t)))/(Es*sqrt(2*pi));
 a5 = exp(-((Rp.^2)/(2*(sigma^2+(2*D*t)))));

a6 = (4.*Na./Q).*sqrt((2*Es./(q*Na)).*(Vbi-Vbs));
a8 = (8.*Na*Es/(q*Q^2)).*(Vbi-Vbs);
VT1= (pibn-delta-(a1.*(a2+a3))-(a4*a5)-a6+a8)./alpha
plot(alpha,VT1,'r');
end;
hold on;
for Na =1e14;
a1 = (q*Q*Rp)/(2*Es);
a2 = erf(Rp/(sqrt(2*sqrt(sigma^2+(2*D*t)))));
a3 = 1-((2.*Na/Q).*sqrt((2.*Es/(q.*Na)).*(Vbi-Vbs)));
a4 = (q*Q*sqrt(sigma^2+(2*D*t)))/(Es*sqrt(2*pi));
a5 = exp(-(Rp.^2/(2*(sigma^2+(2*D*t)))));
a6 = (4.*Na/Q).*sqrt((2*Es./(q*Na)).*(Vbi-Vbs));
a8 = (8.*Na*Es/(q*Q^2)).*(Vbi-Vbs);
VT2= (pibn-delta-(a1.*(a2+a3))-(a4*a5)-a6+a8)./alpha;
plot(alpha,VT2,'g');
end;
hold on;
for Na =4e14;
a1 = (q*Q*Rp)/(2*Es);
a2 = erf(Rp/(sqrt(2*sqrt(sigma^2+(2*D*t)))));
a3 = 1-((2.*Na/Q).*sqrt((2.*Es/(q.*Na)).*(Vbi-Vbs)));
a4 = (q*Q*sqrt(sigma^2+(2*D*t)))/(Es*sqrt(2*pi));
a5 = exp(-((R_p^2/(2*(sigma^2+(2*D*t))))));

a6 = (4.*Na/Q).*sqrt((2*Es./(q*Na)).*(Vbi-Vbs));

a8 = (8.*Na*Es/(q*Q^2)).*(Vbi-Vbs);

VT3 = (pibn-delta-(a1.*(a2+a3))-(a4*a5)-a6+a8)/alpha

plot(alpha,VT3,'b');

end;

title('Variation of Scaling factor Vs Threshold voltage');

xlabel('Scaling factor, alpha');

ylabel('Threshold voltage, VT (V)');

title('Threshold voltage Vs Scaling factor');

legend('Na=2e12','Na=1e14','Na=4e14');

**Variation of channel length versus cutoff frequency**

Clc;

clear all;

for alpha = 1;

q = 1.6e-19;

Z = 500e-4./alpha;

Q = 4e14;

sigma = 739e-8;

u = 300;

L = 1:0.1:4;

D = 0.74e-15;

t=1273;
$eo = 9.7;$

$es = 8.858e^{-14};$

$Es = eo*es;$

$T = 300;$

$Nb = 1e16.*alpha;$

$Nd = 1.38e18.*alpha;$

$Nc = 4.3e14*T^{1.5}.*alpha;$

$Nv = 8.9e15*T^{1.5}.*alpha;$

$Ns = 1e12.*alpha;$

$Eg = 3.40;$

$a = 0.3e^{-4};$

$k = 1.38e^{-23};$

$Vt = ((k*T)/q)/alpha;$

$Vbs = (-6)/alpha;$

$Na = 1e12.*alpha;$

$pib = 2;$

$delta = 0.1;$

$Rp = 1767e^{-8};$

$Ni = (sqrt(Nc*Nv)*(exp(-Eg/(2*Vt)))).*alpha;$

$Vbi = (Vt*log(Nd/Ni))/alpha;$

$V = 2./alpha;$

$Vds = 6./alpha;$

$Vgs = -2./alpha;$
Vp=1.45./alpha;
VT=1.75./alpha;
V1=(q*(Q^2))/(8*Na*Es);
V2=((q*Q)*sqrt(sigma^2+(2*D*t)))/sqrt(2*pi*Es);

% calculating transconductance
alpha1=(Rp/(2*sqrt(sigma^2+(2*D*t))))*sqrt(pi/2);
a1=(q*u*Z*Q)/(4*L);
ap=1e7;
a2=(1/(V1*ap));
a3=(1/(V2*(alpha1+1-ap)));
a4=Vgs-VT;
gm=a1.*(a2+a3).*a4;

% calculating Cgs
N=(Vbi-Vgs+Vds);
R=(Vbi-Vgs);
M=(4*alpha1*Es)/(q*Q*Rp);
A2=erf(Rp/(2*sqrt(sigma^2+(2*D*t))))-alpha1;
A3=1-exp(-
(Rp/(sqrt(2*(sigma^2+(2*D*t))))))^2)*alpha1*erf(Rp/(sqrt(2*(sigma^2+(2*D*t)))));
A1=alpha1^2+A3;
c=(q*Q*Z.*L)./2;
c1=M/sqrt(2*((M*N)+A1));
c2=(sqrt(N)/2*(sqrt(N)-sqrt(R))^2);
c3=sqrt((M*N)+A1)/sqrt(R);
c4=M*(sqrt(N)-sqrt(R))/sqrt((M*R)+A1);
c5=sqrt((M*R)+A1)/sqrt(R);
c6= (1/Q)*sqrt((2*Ns*Es)/q);
c7=(2*(sqrt(N)-sqrt(R)/sqrt(R)));
c8=(Vds)/(sqrt(R*N));
c9=((pi/2)*Es*Z);
Cgs=(c*(c1+c2*(c3-c4-c5-(c6*(c7+c8))))+c9)./alpha
Ft=gm./(2*pi*Cgs).*alpha;
plot(L,Ft,'r');
end;
hold on;
for alpha = 2;
q = 1.6e-19;
Z = 500e-4./alpha;
Q = 4e14;
sigma = 739e-8;
u = 300;
L = 1:0.1:4;
D = 0.74e-15;
t=1273;
eo = 9.7;
es = 8.858e-14;
Es = eo*es;

T = 300;

Nb = 1e16.*alpha;

Nd = 1.38e18.*alpha;

Nc = 4.3e14*T^1.5.*alpha;

Nv = 8.9e15*T^1.5.*alpha;

Ns= 1e12.*alpha;

Eg = 3.40;

a = 0.3e-4;

k = 1.38e-23;

Vt = ((k*T)/q)./alpha;

Vbs= (-6)./alpha;

Na = 1e12.*alpha;

pib = 2;

delta = 0.1;

Rp=1767e-8;

Ni = (sqrt(Nc*Nv)*(exp(-Eg/(2*Vt))).*alpha;

Vbi = (Vt*log(Nd/Ni))./alpha;

V=2./alpha;

Vds=6./alpha;

Vgs=-2./alpha;

Vp=1.45./alpha;

VT=1.75./alpha;
V1=(q*(Q^2))/(8*Na*Es);
V2=((q*Q)*sqrt(sigma^2+(2*D*t)))/sqrt(2*pi*Es);

% calculating transconductance
alpha1=(Rp/(2*sqrt(sigma^2+(2*D*t))))*sqrt(pi/2);
a1=(q*u*Z*Q)/(4*L);
ap=1e7;
a2=(1/(V1*ap));
a3=(1/(V2*(alpha1+1-ap)));
a4=Vgs-VT;
gm=a1.*(a2+a3).*a4;

% calculating Cgs
N=(Vbi-Vgs+Vds);
R=(Vbi-Vgs);
M=(4*alpha1*Es)/(q*Q*Rp);
A2=erf(Rp/(2*sqrt(sigma^2+(2*D*t))))-alpha1;
A3=1-exp(-
(Rp/(sqrt(2*(sigma^2+(2*D*t))))^2)*alpha1*erf(Rp/(sqrt(2*(sigma^2+(2*D*t))))));
A1=alpha1^2+A3;
c=(q*Q*Z.*L)./2;
c1=M/sqrt(2*((M*N)+A1));
c2=(sqrt(N)/2*(sqrt(N)-sqrt(R))^2);
c3=sqrt((M*N)+A1)/sqrt(R);
c4=M*(sqrt(N)-sqrt(R))/sqrt((M*R)+A1);
\[ c_5 = \frac{\sqrt{M + A_1}}{\sqrt{R}}; \]
\[ c_6 = \frac{(1/Q)\sqrt{2N_sE_s}}{q}; \]
\[ c_7 = \frac{2(\sqrt{N} - \sqrt{R}/\sqrt{R})}{\sqrt{R}}; \]
\[ c_8 = \frac{V_{ds}}{\sqrt{R}}; \]
\[ c_9 = \frac{\pi/2 \cdot E_s}{Z}; \]
\[ C_{gs} = \left( c_1 + c_2 (c_3 - c_4 - c_5 (c_6 (c_7 + c_8))) + c_9 \right)/\alpha \]
\[ F_{t1} = \frac{g_m}{2\pi C_{gs}} \cdot \alpha; \]
\[ \text{plot}(L,F_{t1},'b'); \]
\[ \text{end}; \]
\[ \text{hold on}; \]
\[ \text{for} \alpha = 3; \]
\[ q = 1.6e^{-19}; \]
\[ Z = 500e^{-4}/\alpha; \]
\[ Q = 4e14; \]
\[ \sigma = 739e-8; \]
\[ u = 300; \]
\[ L = 1:0.1:4; \]
\[ D = 0.74e-15; \]
\[ t = 1273; \]
\[ e_0 = 9.7; \]
\[ e_s = 8.858e-14; \]
\[ E_s = e_0 \cdot e_s; \]
\[ T = 300; \]
Nb = 1e16.*alpha;
Nd = 1.38e18.*alpha;
Nc = 4.3e14*T^1.5.*alpha;
Nv = 8.9e15*T^1.5.*alpha;
Ns = 1e12.*alpha;
Eg = 3.40;
a = 0.3e-4;
k = 1.38e-23;
Vt = ((k*T)/q)./alpha;
Vbs = (-6)./alpha;
Na = 1e12.*alpha;
pi_b = 2;
delta = 0.1;
Rp = 1767e-8;
Ni = (sqrt(Nc*Nv)*(exp(-Eg/(2*Vt))).*alpha;
Vbi = (Vt*log(Nd/Ni))./alpha;
V = 2./alpha;
Vds = 6./alpha;
Vgs = -2./alpha;
Vp = 1.45./alpha;
VT = 1.75./alpha;
V1 = (q*(Q^2))/(8*Na*Es);
V2 = ((q*Q)*sqrt(sigma^2+(2*D*t)))/sqrt(2*pi*Es);
\[
\text{% calculating transconductance}
\]
\[
\alpha_1 = \frac{R_p}{2\sqrt{\sigma^2 + (2D_t)t}} \times \sqrt{\pi/2};
\]
\[
a_1 = \frac{q u Z Q}{4L};
\]
\[
ap = 1e7;
\]
\[
a_2 = \frac{1}{V_1 ap};
\]
\[
a_3 = \frac{1}{V_2 (\alpha_1 + 1 - ap)};
\]
\[
a_4 = V_{gs} - V_T;
\]
\[
g_m = a_1 \times (a_2 + a_3) \times a_4;
\]
\[
\text{% calculating Cgs}
\]
\[
N = (V_{bi} - V_{gs} + V_{ds});
\]
\[
R = (V_{bi} - V_{gs});
\]
\[
M = \frac{4\alpha_1 E_s}{q Q R_p};
\]
\[
A_2 = \text{erf} \left( \frac{R_p}{2\sqrt{\sigma^2 + (2D_t)t}} \right) - \alpha_1;
\]
\[
A_3 = 1 - \exp \left( - \left( \frac{R_p}{\sqrt{2(\sigma^2 + (2D_t)t)}} \right)^2 \right) 2\alpha_1 \times \text{erf} \left( \frac{R_p}{\sqrt{2(\sigma^2 + (2D_t)t)}} \right);
\]
\[
A_1 = \alpha_1^2 + A_3;
\]
\[
c = \frac{q Q Z L}{2};
\]
\[
c_1 = M / \sqrt{2((M N) + A_1)};
\]
\[
c_2 = \sqrt{N} / 2 \times (\sqrt{N} - \sqrt{R})^2;
\]
\[
c_3 = \sqrt{(M N) + A_1} / \sqrt{R};
\]
\[
c_4 = M \times (\sqrt{N} - \sqrt{R}) / \sqrt{((M R) + A_1)};
\]
\[
c_5 = \sqrt{((M R) + A_1)} / \sqrt{R};
\]
\[
c_6 = \frac{1}{Q} \times \sqrt{2N_s E_s / q};
\]
\[ c7 = 2(\sqrt{N} - \sqrt{R}/\sqrt{R}) \]

\[ c8 = (V_{ds})/(\sqrt{R*N}) \]

\[ c9 = ((\pi/2)*E_s*Z) \]

\[ C_{gs} = c*(c1+c2*(c3-c4-c5-(c6*(c7+c8)))+c9)/\alpha \]

\[ Ft2 = g_m/(2*\pi*C_{gs})*\alpha \]

\[ \text{plot}(L,Ft2,'b'); \]

\[ \text{end}; \]

\[ \text{xlabel('Length,L (um)');} \]

\[ \text{ylabel('Frequency,Ft (GHz)');} \]

\[ \text{title('Variation of Frequency Vs Length');} \]

\[ \text{legend('Unscaled alpha=1','Scaled alpha=2','Scaled alpha=3');} \]

**Variation of channel length versus time delay**

\[ \text{Clc;} \]

\[ \text{Clear all;} \]

\[ \text{for alpha=1;} \]

\[ q = 1.6e-19; \]

\[ Z = 2e-4/\alpha; \]

\[ Q = 2e11; \]

\[ \text{sigma = 0.72e-4;} \]

\[ u = 300; \]

\[ L = 1:0.1:4; \]

\[ D = 0.74e-15; \]

\[ t=1273; \]
Vds = 6./alpha;

eo = 9.7;
es = 8.858e-14;
es = eo*es;
T = 300;
Nb = 1e16.*alpha;
Nd = 1e16.*alpha;
Nc = 4.3e14*T^1.5.*alpha;
Nv = 8.9e15*T^1.5.*alpha;
Ns=11e12.*alpha;
Eg = 3.40;
a = 0.4e-4;
k = 1.38e-23;
Vt = ((k*T)/q)./alpha;
Vbs= 6./alpha;
Na = 1e12.*alpha;
pib = 2;
delta = 0.1;
Vgs=0./alpha;

% calculating the value of Rds

Rp=1767e-8;
alpha1=(Rp/(2*sqrt(sigma^2+(2*D*t))))*sqrt(pi/2);
Vp = q*Q*a^2/(2*Es*sqrt(sigma^2+(2*D*t))*(sqrt(2*pi)));
V1 = (q*Q^2)/(8*Na*Es);
V2 = q*Q*sqrt(sigma^2+(2*D*t))/(sqrt(2*pi*Es));
Ni=1e12;
Vbi=1.45;
ap=1.2;
d=(q*u*Q*Z)/(L*2);
d1=(1+alpha1);
d2=sqrt(ap^2-(Vp/V1));
d3=sqrt((alpha1+1-ap)^2-(Vp/V2));
d4=(pi*u)/2;
d5=(2*Es*q*Q*Vbi)/sqrt((sigma^2+(2*D*t))*2*pi);
Rds=((d*(d1-d2-d3)+d4*(d5)).^1).*alpha;

% calculating Cgd
N=Vbi-Vgs+Vds;
R=Vbi-Vgs;
M=(4*alpha1*Es)/(q*Q*Rp);
A2=erf(Rp/(2*sqrt(sigma^2+(2*D*t))))-alpha1;
A3=1-exp(-
(Rp/(sqrt(2*(sigma^2+(2*D*t))))))^2)*alpha1*erf(Rp/(sqrt(2*(sigma^2+(2*D*t)))));
A1=alpha1^2+A3;
b=(q*Q*Z*L)/2;
b1=M/sqrt(2*((M*N)+A1));
b2=(sqrt(R)/2*((sqrt(N)-sqrt(R))^2));
b3=sqrt((M*R)+A1)/sqrt(N);
b4=M*(sqrt(N)-sqrt(R))/sqrt((M*N)+A1);
b5=sqrt((M*N)+A1)/sqrt(N);
b6= (1/Q)*sqrt((2*Ns*Es)/q);
b7=(2*(sqrt(N)-sqrt(R))/(sqrt(R)));
b8=(Vds)/(sqrt(R*N));
b9=((pi/2)*Es*Z);

Cgd=(b*(b1+b2*(b3-b4-b5-(b6*(b7-b8))))+b9)./10*alpha

% calculating Cgs

c=(q*Q*Z*L)/2;
c1=M/sqrt(2*((M*N)+A1));
c2=(sqrt(N)/2*(sqrt(N)-sqrt(R))^2);
c3=sqrt((M*N)+A1)/sqrt(R);
c4=M*(sqrt(N)-sqrt(R))/sqrt((M*R)+A1);
c5=sqrt((M*R)+A1)/sqrt(R);
c6= (1/Q)*sqrt((2*Ns*Es)/q);
c7=(2*(sqrt(N)-sqrt(R))/sqrt(R));
c8=(Vds)/(sqrt(R*N));
c9=((pi/2)*Es*Z);

Cgs=(c*(c1+c2*(c3-c4-c5-(c6*(c7+c8)))+c9)/10*alpha;

Td=(Rds.*(Cgs+Cgd))./alpha;

plot(L,Td,'r');

end;
hold on;
for alpha=1.5;
q = 1.6e-19;
Z = 2e-4./alpha;
Q = 2e11;
sigma = 0.72e-4;
u = 300;
L = 1:0.1:4;
D = 0.74e-15;
t=1273;
Vds = 6./alpha;
eo = 9.7;
es = 8.858e-14;
Es = eo*es;
T = 300;
Nb = 1e16.*alpha;
Nd = 1e16.*alpha;
Nc = 4.3e14*T^1.5.*alpha;
Nv = 8.9e15*T^1.5.*alpha;
Ns=11e12.*alpha;
Eg = 3.40;
a = 0.4e-4;
k = 1.38e-23;
Vt = ((k*T)/q)./alpha;
Vbs= 6./alpha;
Na = 1e12.*alpha;
pib = 2;
delta = 0.1;
Vgs=0./alpha;

% calculating the value of Rds
Rp=1767e-8;

alpha1=(Rp/(2*sqrt(sigma^2+(2*D*t))))*sqrt(pi/2);

Vp = q*Q*a^2/(2*Es*sqrt(sigma^2+(2*D*t))*(sqrt(2*pi)));

V1=(q*Q^2)/(8*Na*Es);

V2 = q*Q*sqrt(sigma^2+(2*D*t))/(sqrt(2*pi*Es));

Ni=1e12;

Vbi=1.45;
ap=1.2;

d=(q*u*Q*Z)./(L*2);

d1=(1+alpha1);

d2=sqrt(ap^2-(Vp/V1));

d3=sqrt((alpha1+1-ap)^2-(Vp/V2));

d4=(pi*u)/2;

d5=(2*Es*q*Q*Vbi)/sqrt((sigma^2+(2*D*t))*2*pi);

Rds=((d*(d1-d2-d3)+d4*(d5)).^1).*alpha;
% calculating Cgd

N = Vbi - Vgs + Vds;
R = Vbi - Vgs;
M = (4*alpha1*Es)/(q*Q*Rp);
A2 = erf(Rp/(2*sqrt(sigma^2+(2*D*t))))-alpha1;
A3 = 1 - exp(-((Rp/(sqrt(2*(sigma^2+(2*D*t)))))^2)-
2*alpha1*erf(Rp/(sqrt(2*(sigma^2+(2*D*t)))));
A1 = alpha1^2 + A3;
b = (q*Q*Z*L)/2;
b1 = M/sqrt(2*((M*N)+A1));
b2 = (sqrt(R)/2*((sqrt(N)-sqrt(R))^2));
b3 = sqrt((M*R)+A1)/sqrt(N);
b4 = M*(sqrt(N)-sqrt(R))/sqrt((M*N)+A1);
b5 = sqrt((M*N)+A1)/sqrt(N);
b6 = (1/Q)*sqrt((2*Ns*Es)/q);
b7 = (2*(sqrt(N)-sqrt(R))/(sqrt(R)));
b8 = (Vds)/(sqrt(R*N)));
b9 = ((pi/2)*Es*Z);
Cgd = (b*(b1+b2*(b3-b4-b5-(b6*(b7-b8)))+b9)/10*alpha

% calculating Cgs

c = (q*Q*Z*L)/2;
c1 = M/sqrt(2*((M*N)+A1));
c2 = (sqrt(N)/2*(sqrt(N)-sqrt(R))^2);
c3 = sqrt((M*N)+A1)/sqrt(R);
c4 = M*(sqrt(N)-sqrt(R))/sqrt((M*R)+A1);
c5 = sqrt((M*R)+A1)/sqrt(R);
c6 = (1/Q)*sqrt((2*Ns*Es)/q);
c7 = (2*(sqrt(N)-sqrt(R))/sqrt(R));
c8 = (Vds)/(sqrt(R*N));
c9 = ((pi/2)*Es*Z);
Cgs = (c*(c1+c2*(c3-c4-c5-(c6*(c7+c8))))+c9)/10*alpha
Td1 = (Rds.*(Cgs+Cgd))./alpha;
plot(L,Td1,'b');
end;
hold on;
for alpha=1.8;
q = 1.6e-19;
Z = 2e-4./alpha;
Q = 2e11;
sigma = 0.72e-4;
u = 300;
L = 1:0.1:4;
D = 0.74e-15;
t = 1273;
Vds = 6./alpha;
eo = 9.7;
es = 8.858e-14;
Es = eo*es;
T = 300;
Nb = 1e16.*alpha;
Nd = 1e16.*alpha;
Nc = 4.3e14*T^1.5.*alpha;
Nv = 8.9e15*T^1.5.*alpha;
Ns=11e12.*alpha;
Eg = 3.40;
a = 0.4e-4;
k = 1.38e-23;
Vt = ((k*T)/q)./alpha;
Vbs= 6./alpha;
Na = 1e12.*alpha;
pib = 2;
delta = 0.1;
Vgs=0./alpha;

% caliculating the value of Rds
Rp=1767e-8;
alpha1=(Rp/(2*sqrt(sigma^2+(2*D*t))))*sqrt(pi/2);
%Rp = alpha1*(2*sqrt(sigma^2+(2*D*t)))/(sqrt(pi/2));
Vp = q*Q*a^2/(2*Es*sqrt(sigma^2+(2*D*t))*(sqrt(2*pi)));
V1=(q*Q^2)/(8*Na*Es);
\[ V_2 = \frac{q \cdot Q \cdot \sqrt{\sigma^2 + (2 \cdot D \cdot t)\pi}}{\sqrt{2 \pi E_s}}; \]

\[ N_i = 1e12; \]

\[ V_{bi} = 1.45; \]

\[ a_p = 1.2; \]

\[ d = \frac{q \cdot u \cdot Q \cdot Z}{L^2}; \]

\[ d_1 = (1 + \alpha_1); \]

\[ d_2 = \sqrt{a_p^2 - \frac{V_p}{V_1}}; \]

\[ d_3 = \sqrt{(\alpha_1 + 1 - a_p)^2 - \frac{V_p}{V_2}}; \]

\[ d_4 = \frac{\pi \cdot u}{2}; \]

\[ d_5 = \frac{2 \cdot E_s \cdot q \cdot Q \cdot V_{bi}}{\sqrt{(\sigma^2 + (2 \cdot D \cdot t)\pi)}_2}; \]

\[ R_{ds} = ((d \cdot (d_1 - d_2 - d_3) + d_4 \cdot (d_5)) \cdot (1 - \alpha)); \]

\% calculating Cgd

\[ N = V_{bi} - V_{gs} + V_{ds}; \]

\[ R = V_{bi} - V_{gs}; \]

\[ M = \frac{4 \cdot \alpha_1 \cdot E_s}{q \cdot Q \cdot R_p}; \]

\[ A_2 = \text{erf}(R_p/(2\sqrt{\sigma^2 +(2 \cdot D \cdot t)})) - \alpha_1; \]

\[ A_3 = 1 - \exp\left(-\frac{R_p}{\sqrt{2 \cdot (\sigma^2 + (2 \cdot D \cdot t))}}\right)^2 - \frac{2 \cdot \alpha_1 \cdot \text{erf}(R_p/(\sqrt{2 \cdot (\sigma^2 + (2 \cdot D \cdot t))}))}{2}; \]

\[ A_1 = \alpha_1 \cdot (2 + A_3); \]

\[ b = \frac{q \cdot Q \cdot Z \cdot L}{2}; \]

\[ b_1 = M/\sqrt{2 \cdot (N + A_1)}; \]

\[ b_2 = \sqrt{R}/2 \cdot (\sqrt{N} - \sqrt{R})^2; \]

\[ b_3 = \frac{\sqrt{R}}{\sqrt{2 \cdot (N + A_1)}}; \]
b4=M*(sqrt(N)-sqrt(R))/sqrt((M*N)+A1);
b5=sqrt((M*N)+A1)/sqrt(N);
b6= (1/Q)*sqrt((2*Ns*Es)/q);
b7=(2*(sqrt(N)-sqrt(R))/(sqrt(R)));
b8=(Vds)/(sqrt(R*N));
b9=((pi/2)*Es*Z);
Cgd=(b*(b1+b2*(b3-b4-b5-(b6*(b7-b8))))+b9)./10*alpha 
% calculating Cgs

c=(q*Q*Z*L)/2;
c1=M/sqrt(2*((M*N)+A1));
c2=(sqrt(N)/2*(sqrt(N)-sqrt(R))^2);
c3=sqrt((M*N)+A1)/sqrt(R);
c4=M*(sqrt(N)-sqrt(R))/sqrt((M*R)+A1);
c5=sqrt((M*R)+A1)/sqrt(R);
c6= (1/Q)*sqrt((2*Ns*Es)/q);
c7=(2*(sqrt(N)-sqrt(R))/sqrt(R));
c8=(Vds)/(sqrt(R*N));
c9=((pi/2)*Es*Z);
Cgs=(c*(c1+c2*(c3-c4-c5-(c6*(c7+c8))))+c9)./10*alpha
Td2=(Rds.*(Cgs+Cgd))./alpha;
plot(L,Td2,'b');
end;
xlabel('Length, L (um)');

ylabel('Time delay, T_d (ns)');

title('Variation of Length Vs Time delay');

legend('Unscaled alpha=1','Scaled alpha=1.5','Scaled alpha=2');

**Variation of drain to source voltage versus power**

clear all;

cle;

for alpha = 1;

q = 1.6e-19;

Q = 5e12;

u = 300;

Z = 500e-4./alpha;

L = 0.5e-4./alpha;

Na = 1e12.*alpha;

Nd = 1.38e18.*alpha;

Es = 9.7*8.854e-14;

T=300;

Nv = (8.9e15*T^1.5).*alpha;

Nc = (4.3e14*T^1.5).*alpha;

k = 1.38e-23;

Vt = (k*T)/q;

Ni = (sqrt(Nc.*Nv)*(exp(-Es/(2*Vt)))).*alpha;

Vbi = (Vt*log(Nd/Ni))./alpha;
Vbs = -6./alpha;
Vgs = -4./alpha;
sigma = 739e-8;
Rp = 1767e-8;
pibn = 2;
delta = 0.1;
Vds=1:0.1:3;

% calculating current
R = (Es*sqrt(2*pi))/(q*Q*sigma);
c1 = erf(Rp/(sigma*sqrt(2)));
a1 = (q*Q*u.*Z)/(2.*L);
a0 = Vds.*(1+alpha);
a2 = -(2*q.*Na.^2)/(3*Q*Es).*)((2*Es)/(q.*Na).*(Vbi-Vbs+Vds)).^1.5;
a3 = (2*q.*Na.^2)/(3*Q*Es).*)((2*Es)/(q.*Na).*(Vbi-Vbs)).^1.5;
a4 = -((q*Q*sigma).*)((sqrt(2/pi)).*((alpha.^2-(2.*alpha.*c1)+c1^2+R*(Vds-Vgs+pibn-delta)).^1.5);
a5=((q*Q*sigma).*)((sqrt(2/pi)).*((alpha.^2-(2.*alpha.*c1)+c1^2+R*(Vds-Vgs+pibn-delta)).^1.5);
Ids = (a1.*(a0+a2+a3+a4+a5))./alpha
Pw=(Ids.*Vds);
plot(Vds,Pw,'r');
end;
hold on;
for alpha = 2;
    q = 1.6e-19;
    Q = 5e12;
    u = 300;
    Z = 500e-4./alpha;
    L = 0.5e-4./alpha;
    Na = 1e12.*alpha;
    Nd = 1.38e18.*alpha;
    Es = 9.7*8.854e-14;
    T=300;
    Nv = (8.9e15*T^1.5).*alpha;
    Nc = (4.3e14*T^1.5).*alpha;
    k = 1.38e-23;
    Vt = (k*T)/q;
    Ni = (sqrt(Nc.*Nv)*(exp(-Es/(2*Vt)))).*alpha;
    Vbi = (Vt*log(Nd/Ni))./alpha;
    Vbs = -6./alpha;
    Vgs = -4./alpha;
    sigma = 739e-8;
    Rp = 1767e-8;
    pibn = 2;
    delta = 0.1;
Vds=1:0.1:3;

% calculating current

R = (Es*sqrt(2*pi))/(q*Q*sigma);
c1 = erf(Rp/(sigma*sqrt(2)));
a1 = (q*Q*u.*Z)/(2.*L);
a0 = Vds.*(1+alpha);
a2 = -(2*q.*Na.^2)/(3*Q*Es).*((2*Es)/(q.*Na).*(Vbi-Vbs+Vds)).^1.5;
a3 = (2*q.*Na.^2)/(3*Q*Es).*((2*Es)/(q.*Na).*(Vbi-Vbs)).^1.5;
a4 = -((q*Q*sigma).*(sqrt(2/pi)).*(alpha.^2-(2.*alpha.*c1)+c1^2+R*(Vds-Vgs+pin-delta)).^1.5);
a5 = ((q*Q*sigma).*(sqrt(2/pi)).*(alpha.^2-(2.*alpha.*c1)+c1^2+R*(-Vgs+pin-delta)).^1.5);

Ids1 = (a1.*(a0+a2+a3+a4+a5))./alpha;

End;

Pw=(Ids1.*Vds);

plot(Vds,Pw,'b');

hold on;

for alpha = 3;

q = 1.6e-19;
Q = 5e12;
u = 300;
Z = 500e-4./alpha;
L = 0.5e-4./alpha;
Na = 1e12.*alpha;
Nd = 1.38e18.*alpha;
Es = 9.7*8.854e-14;
T=300;
Nv = (8.9e15*T^1.5).*alpha;
Nc = (4.3e14*T^1.5).*alpha;
k = 1.38e-23;
Vt = (k*T)/q;
Ni = (sqrt(Nc.*Nv)*(exp(-Es/(2*Vt)))).*alpha;
Vbi = (Vt*log(Nd/Ni))./alpha;
Vbs = -6./alpha;
Vgs = -4./alpha;
sigma = 739e-8;
Rp = 1767e-8;
pibn = 2;
delta = 0.1;
Vds=1:0.1:3;

% calculating current

R = (Es*sqrt(2*pi))/(q*Q*sigma);
c1 = erf(Rp/(sigma*sqrt(2)));
a1 = (q*Q*u.*Z)/(2.*L);
a0 = Vds.*(1+alpha);
a2 = -(2*q.*Na.^2)/(3*Q*Es).*((2*Es)/(q.*Na).*((Vbi-Vbs+Vds)).^1.5);
a3 = (2*q.*Na.^2)/(3*Q*Es).*((2*Es)/(q.*Na).*(Vbi-Vbs)).^1.5;

a4 = -((q*Q*sigma).*(sqrt(2/pi)).*(alpha.^2-(2.*alpha.*c1)+c1^2+R*(Vds-Vgs+pin-delta)).^1.5);

a5=((q*Q*sigma).*(sqrt(2/pi)).*(alpha.^2-(2.*alpha.*c1)+c1^2+R*(-Vgs+pin-delta)).^1.5);

Ids2 = (a1.*(a0+a2+a3+a4+a5))./alpha

Pw=(Ids2.*Vds);

plot(Vds,Pw,'b');

end;

xlabel('Drain to source voltage, Vds (V)');

ylabel('Power, Pw (mw)');

title('Power Vs Drain to source voltage');

legend('Unscaled alpha=1','Scaled alpha=2','Scaled alpha=3');