CHAPTER 1

SPACE RADIATION ENVIRONMENT AND ITS EFFECT ON SEMICONDUCTOR DEVICES

1.1 INTRODUCTION

The study of radiation effects is an interdisciplinary subject centered on high energy particle physics and solid state physics. The need for this type of study arose as a matter of urgency only in the late 1950’s when semiconductor technology began to be used in space and military equipments. These two environments - nuclear weapons and space - provide exposure to radiations that leave many active semiconductor devices severely damaged. The sources for these radiations will be either terrestrial or the outer space. The terrestrial radiation sources are nuclear weapons, nuclear reactors, controlled fusion etc, whereas for the outer space, the cosmic rays, solar particles, trapped particles in the earth’s magnetic fields etc. The high energy space radiation environment consists of a variety of particle species, including solar, galactic, and trapped protons, trapped electrons, and heavy ions from Solar Particle Events (SPE) and the Galactic Cosmic Radiation (GCR). A high energy particle interacts with matter in different ways depending on its energy, mass, charge state and the nature of the species. The main interaction mechanisms are elastic and inelastic scattering and nuclear reactions like spallation, fragmentation, and fission. The interaction of the primary radiation with the shielding or device material leads to secondaries such as neutrons, protons, mesons, atomic recoils, nuclear fragments, and electromagnetic radiation. The various types of radiations from space that affects
semiconductor devices are, gamma rays, x-rays, alpha particles, beta particles, electrons, positrons, neutrons, protons and as well as a lower percentage of heavy particles like nitrogen, oxygen, iron etc.

1.2 SOURCES OF SPACE RADIATION

The space radiation environment consists of different kinds of particles with energies ranging from keV to GeV and beyond. As they pass through the solar system, most of them are trapped in the magnetic fields of the planetary system. Such trapped radiation fields around earth are known as Van Allen belts. The main sources of energetic particles radiation in earth space (Stassinopoulos and Raymond 1988, Claeys and Simoen 2002, Holmes-Siedle and Adams 2004, Scherer et al 2005) that are of concern to spacecraft designers are: (i) Trapped radiation - charged particles as they pass through earth’s magnetic field are trapped by the magnetic field and constitute the radiation belts - protons, electrons and heavy ions. (ii) Cosmic radiation - they are the low flux, energetic and heavy ions from outer space with energies beyond TeV and includes protons, nitrogen, oxygen, iron etc. (iii) Solar flares - during the sudden bursts of the sun, huge quantities of energetic particles like protons, electrons, with small fluxes of alpha particles and heavy ions are ejected. Energies range to hundreds of MeV.

The levels of all the radiation sources are affected by the activity of the sun. The solar cycle is divided into two activity phases: the solar minimum and the solar maximum. An average cycle lasts about eleven years with the length varying from nine to thirteen years. In addition to this broad classification, there is plasma filling the entire space, consisting mainly of protons and electrons with energies up to about 100 keV and fluxes around $10^{12} \text{ cm}^{-2}\text{s}^{-1}$. The plasma can cause spacecraft charging. This charging and subsequent discharging can affect the internal electronics.
1.3 BASIC RADIATION DAMAGE MECHANISMS IN SEMICONDUCTOR MATERIALS AND DEVICES

1.3.1 Interaction of radiation with matter

Photons or ions of high energy when passing through matter lose energy through different kinds of interaction and scattering mechanisms. The energy deposited by the passage of radiations is responsible for variety of damage effects such as ionization, and displacement of atoms from the lattice sites, resulting in the degradation of device parameters. A distinction can be made between ionization damage, which creates free electron-hole pairs, and displacement damage, which occurs when atoms are removed from their natural lattice site, leaving behind a lattice vacancy. Ionization requires far lower energies than it is necessary for displacement damage. There are other radiation effects such as SEE (Single Event Effect), SEU (Single Event Upset), latch up and gate rupture. These effects are discussed in section 1.4.3 in detail.

1.3.2 Nomenclature

An energetic photon or particle (ion) traveling through a solid state system can lose its energy in various ways, whereby the amount of energy deposited not only depends on the projectile mass and energy but also on the atomic number and mass of the target material. The energy deposited per gram of material is called the dose (D) and is expressed in rads or Grays, whereby (Claeys and Simoen 2002):

\[
1 \text{ rad} = 100 \text{ erg/g} = 6.24 \times 10^{13} \text{ eV/g} \tag{1.1}
\]

\[
1 \text{ Gray} = 1 \text{ J/Kg} = 100 \text{ rad} \tag{1.2}
\]
It is clear from the definition that the energy loss also depends on the density of the target. So one has to differentiate between rad(Si) and rad(SiO₂) for silicon and its oxide, respectively, and the conversion factors are 1 rad(Si) = 0.58 rad(SiO₂) = 0.94 rad(GaAs). The particle density impinging on the material per unit of area and time is called the flux (φ, in units of particles/cm²s), while the flux integrated over the total exposure time is named the fluence Φ, in units of particles/cm².

1.4 RADIATION EFFECTS ON ELECTRONIC DEVICES

The use of microelectronic devices in both civilian and military spacecrafts requires that these devices preserve their functionality in the hostile space environment throughout the mission life. Thus, because of the distinctive nature of the radiation environment, it is important to understand the effects of radiation on microelectronic devices and circuits used in space systems. Irradiation can produce lattice defects which degrade the material and induce serious degradation in devices affecting its performance. The final result will depend upon the type of radiation, the rate of energy deposition in the material, the type of material, its particular contribution to the device function, and the physical principles upon which the function of the device is based. It is important to define a degradation parameter for each characteristic of the material (Billington et al 1961). It is generally defined as the change of the characteristic with the total irradiation dose for ionization induced damages or with the particle fluence for displacement induced damages. Such degradation parameter will be termed as macroscopic, since degradation is defined without reference to details of microscopic damages created by irradiation.

The effects from the natural space radiation environment may be divided into two categories - long term and short term
(Srour and Mcgarrity 1988, Weatherford and Anderson 2003). The long term effects have two separate concerns - ionizing and non-ionizing damage. Short term effects are concerned primarily with single particle ionization and/or secondary particle formation. One should note that even short term effects may be permanent (i.e. destructive single particle events). One may view ionizing radiation effects in space electronics in two parts - total ionizing dose (TID) and single event effects (SEE). In the following, the different types of semiconductor damage will be analyzed and examples and data for the most widely applied and studied Si and GaAs electronic devices will be provided.

1.4.1 Ionizing Radiation Damage

When energetic photons like $\gamma$ and X-rays or particles, interact with solid state matter they cause ionization. Depending on the photon energy $E_{ph}$, different fundamental interactions can take place which result in the creation of free carriers in the material. In case of a semiconductor, a valence band electron is emitted into the conduction band across the band gap $E_G$, leaving behind a free hole. The net result is the creation of a free electron-hole pair. The number of electron-hole pairs produced in a medium by a particle with a certain ionization energy loss depends on the energy required for creating a pair.

1.4.2 Total Ionizing Dose

Total Ionizing Dose (TID) is a long-term degradation of electronics due to the cumulative energy deposited in a material. Typical effects include parametric failures, or variations in device parameters such as leakage current, threshold voltage, etc. or functional failures (Srour 1999). Significant sources of TID exposure in the space environment include trapped electrons, trapped protons, and solar protons. A common ionization effect is the gradual shift in
the parameters of electronic components leading to circuit failures. For very sensitive microcircuits ~1000 rads(Si) is enough to cause circuit failure (Foster 2003). For hardened electronics the failure dose can be as high as 10 Mega rad(Si). Shielding is usually used to reduce the ionization dose. Aluminium shields can effectively attenuate electrons and low energy protons. However high energy protons (>30 MeV) cannot be shielded.

Insulator films are often used in solid state devices, often acting as stand off layers which act as barriers to arrest charge motion between two layers of semiconductor or conductor. A prime threat of high energy and low energy radiation, particle and photon type, to electronic and optoelectronic devices is that it may (i) temporarily lower that barrier, (ii) trap some of the charge traveling across the oxide and freeze it in place, producing a semi-permanent charge sheet (this will have its own built in field which will bend bands and so affect conductivity in charge sensitive layers around it); (iii) disturb the labile bonds which often occur at the interfaces especially insulator-semiconductor interfaces. Effects (ii) & (iii) constitute two of the most serious TID effects in microelectronic semiconductor devices.

GaAs devices in general are relatively immune to total dose effects resulting from the deposition of ionizing energy. This is due to the absence of an oxide that can trap charge and alter the operation of the device. Tests have shown immunity to total dose effects up to 100 Mrad(GaAs). In contrast with the relative immunity of GaAs devices to total dose effects, transient, high dose rate pulses can severely affect these devices. GaAs devices and circuits are typically fabricated on semi-insulating GaAs substrates, which provide a natural isolation between individual transistors on the chip. However, in a transient radiation environment, this attractive feature becomes a liability because the transient photocurrents generated in the substrate are much larger than the transients generated elsewhere in the device. Under these conditions,
upset levels in GaAs devices can be of the order of $10^{10}$ rad(GaAs)/s, or even less. Fortunately, these effects can be minimized by properly placing bonding pads and metal interconnects, and using various types of blocking layers (Meulenberg et al 1988).

1.4.3 Single Event Effects

Single Event Effects (SEEs) occur when single energetic heavy ion strikes a material, depositing sufficient energy at high densities either through its prime strike (e.g., direct ionization via GCR) or by the secondary particles that occur from the strike (e.g., indirect ionization via protons) to cause an effect in the device (Johnston 1998). The single particle impact gives rise to an ionized track of electron-hole pairs along the particle’s trajectory through a semiconductor material. Microcircuits that are particularly sensitive to SEE can also be upset by protons and alpha particles, even though their energy loss per unit length is significantly less than that of energetic heavy ions (Weatherford et al 1991, Reed et al 1997). The different types of single event effects include:

Single Event Upsets (SEUs) - An energetic particle passing through a digital electronic device causes an unplanned change in its logic state. Afterward, the device may be re-written into the intended state.

Single Event Latch-ups (SELs) - In this case, the device is latched into one logic state and will not change states in response to a logic signal. This occurs when the SEU activates a parasitic circuit in the device which connects its power supply to ground. If the current is externally limited, no permanent damage occurs and the operability of the device can be recovered by cycling the power.
Single Event Burnouts (SEBs) - In this case, the current is not limited and the device is destroyed. SEBs occur in power MOSFETs and is the most dangerous form of single event since it leads to permanent failure. Other single event effects, which are not yet well understood, include Single Event Gate Ruptures (SEGRs), Single Event Functionality Interrupts (SEFI), and Single Event Dielectric Ruptures (SEDR).

The many types of SEE may be divided into two main categories: soft errors and hard errors. In general, a soft error occurs when a transient pulse or bit flip in the device causes an error detectable at the device output. Therefore, soft errors are entirely device and design specific, and are best categorized by their impact on the device. Hard errors are not necessarily be physically destructive to the device but may cause permanent functional effects.

Studies of charge collection in GaAs devices have shown the charge generated by a single particle can be collected by a greater variety of mechanisms than in Si devices. In GaAs MESFETs, the collection from deep within the device is limited because the recombination rate in GaAs is high and because the diffusion length is short due to small minority carrier lifetimes. However, relative to Si, this is offset by the fact that more regions of the device are sensitive than in the case of a Si MOSFET. In a GaAs MESFET, the source and drain regions are sensitive to upset as well as the gate region. Collection mechanisms for the various regions in the device are shown in Figure 1.1 and include a back channel turn-on mechanism, a bipolar source-drain collection mechanism, and an ion shunt mechanism. Fortunately, as in the case of photocurrent transients mentioned above, ‘bandgap engineering’ through the deposition of various blocking layers can minimize single event effects.
Figure 1.1  Single particle induced charge collection mechanisms in a GaAs MESFET

1.4.4  Non-ionizing Radiation Damage

Displacement damage dose (DDD) is essentially the cumulative degradation resulting from the displacement of atoms in a material from their lattice position (Huhtinen 2002). Prime sources of DDD exposure include trapped protons, solar protons, radioisotope thermoelectric generator (RTG) neutrons, and to a lesser extent for typically electronic systems, trapped electrons.

DDD often has similar long term degradation characteristics to TID but it should be noted that technologies that are tolerant to TID are NOT necessarily tolerant to DDD (Pease et al 1988). When an atom is pushed out of its lattice position it gives rise to a vacancy and to an interstitial (Frenkel pair). Defect clusters are regions of disorder in the material which result from multiple cumulative displacements. Two adjacent vacancies are collectively
referred to as a di-vacancy and in a similar fashion two adjacent interstitials are referred to as a di-interstitial. Very often, the presence of impurities (whether intentional or not) can lead to the formation of defect-impurity complexes such as vacancy-impurity complexes and interstitial-impurity complexes. Additionally, defects may be either simple (a few atoms displaced together) or defect clusters (longer chains of disordered atoms). In silicon, high energy neutron irradiation can produce defect clusters, whereas low energy electron, gamma-ray and proton irradiations can result in simple defects (Larin 1968). For space environments, displacement effects are primarily the result of high energy protons and electrons. In military and nuclear reactor applications neutrons are a major concern. The presence of vacancies in the crystal lattice is effectively translated to energy states (E_T) in the energy bandgap (E_G). Both deep (E_T ≈ E_C-E_G/2) and shallow (E_T≈ E_C, E_T≈ E_V) level traps are created. All defects in the lattice can be detected via device level measurements of optical and electrical properties (a direct result of the E_T levels). Some of these processes are outlined below and are covered in more detail in (Srour et al 2003 and references therein) and are illustrated in Figure 1.2. Firstly, deep trap levels result in the thermal generation (and recombination) of electron-hole pairs. For generation, a bound state valence electron is promoted from E_V to E_T and then from E_T to E_C. In the case of carrier recombination, the exact opposite process occurs when an electron (in E_C) and a hole (in E_V) both come spatially close to the defect site and are both annihilated at the trap energy, E_T. In this case, E_T must be close to the midgap level to have any appreciable effect. Shallow levels result in the temporary trapping of carriers at the trap energy, E_T. The carriers are usually later returned to their band with no long term recombination taking place. Trap centers (both deep and shallow) may also result in the compensation of dopants or impurities in the lattice. This results in a reduction in the equilibrium majority carrier concentration, which results in an increase in the
collector resistance $R_C$ for bipolar transistors. Defect levels (especially deep levels) can also enable the tunneling of carriers through potential barriers.

![Diagram of bandgap levels](image)

**Figure 1.2** Defects create trap levels in the bandgap that interfere with the dynamics of charge transport via (a) generation, (b) recombination, (c) trapping, (d) compensation and (e) tunneling

This is accomplished through an effective reduction in the barrier height, and width (when under bias). This can cause an increase in the tunneling component of reverse bias currents in pn junctions. Furthermore, radiation induced trap centers can serve as scattering centers and result in a subsequent reduction in carrier mobilities. These effects are amplified at lower temperatures, and higher doping levels where ionized impurity scattering (which can be likened to radiation induced trap centers) dominates over traditional lattice scattering. Depending on the energy level of the trap formed, carrier density, impurity concentration and temperature, any one of the mechanisms described above may dominate, or they may all act in concert. For simple defects (single interstitials or vacancies) mobility and activation energy is dependant on the charge state of the defect. Generation of electron-hole pairs (leading to thermal dark current in detectors), recombination of electron-hole pairs (leading to reduction of minority carrier
lifetime and reduction of efficiency in LEDs and laser diodes), trapping of
carriers, leading to loss in charge transfer efficiency in CCDs (minority carrier
trapping) or carrier removal (majority carrier trapping), compensation of
donors or acceptors, also leading to carrier removal in some devices (for
example the resistance in a lightly doped collector in a bipolar transistor can
increase) and tunneling of carriers, leading to increased current in reverse
biased junctions - particularly for small band gap materials and high electric
fields. Table 1.1 gives the overall radiation effects and parameters generally
used in the device assessment (Daly et al 2003).

Table 1.1  Radiation effects and parameters used in the device assessment

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Parameter</th>
<th>Consequences</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose (TID)</td>
<td>Ionizing dose in material</td>
<td>Threshold voltage shift and leakage currents in CMOS, linear bipolar (note dose-rate sensitivity). Damage to materials. Creation of color centers in optical media.</td>
<td>Electrons, protons, bremsstrahlung</td>
</tr>
<tr>
<td>Displacement damage</td>
<td>Displacement damage</td>
<td>All photonics, e.g CCD transfer efficiency, optocoupler gain, reduction in solar cell efficiency.</td>
<td>Protons, electrons, neutrons, ions</td>
</tr>
<tr>
<td>Displacement damage</td>
<td>Dose Equivalent fluence of 10 MeV protons or 1 MeV electrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single event effects from ions</td>
<td>Events per unit fluence from linear energy transfer (LET) spectra and cross-section versus LET</td>
<td>Memories, microprocessors. Soft errors, latch-up, burn-out, gate rupture, transients in OPAMPs, comparators.</td>
<td>Ions</td>
</tr>
<tr>
<td>Single event effects from nuclear reactions</td>
<td>Events per unit fluence from energy spectra and cross-section versus particle energy</td>
<td>As above</td>
<td>Protons, neutrons</td>
</tr>
</tbody>
</table>
GaAs devices are relatively insensitive to displacement damage effects when compared to Si devices. Generally, this is due to the shorter minority carrier lifetimes and higher doping levels found in GaAs devices and circuits. The longer the lifetime, the higher the mobility, and the smaller the carrier concentration the more effective displacement damage is in altering these parameters. Thus, semiconductor devices with short lifetimes, low mobility, and high carrier concentrations will be relatively immune to displacement damage effects. GaAs has the characteristics of short lifetimes and high mobility. Therefore, one can expect GaAs device to suffer from reduction in mobility and carrier concentration as a result of displacement damage.

1.5 SRIM NIEL CALCULATION

In order to understand the type of damage that radiations can produce in electronic materials and devices it is important to simulate the events that occur in the solid state matter and the amount of energy deposited by the incoming particles or photons. Non Ionizing Energy Loss (NIEL) (Summers et al 1993) is a calculation of the rate of energy loss due to atomic displacements as an incident particle traverses a material. The product of the NIEL and the particle fluence gives the displacement damage energy along the particle trajectories. The finding of a linear relationship between the NIEL and the experimental damage coefficients suggested a method of calculating the radiation response of semiconductor devices in a complex proton space environment, using only one or two ground tests and the energy dependence of the proton NIEL (Messenger et al 1997). NIEL is the direct analog of Linear Energy Transfer (LET) or stopping power for ionization events. The units of NIEL are typically MeV/cm or MeVcm²/g (Messenger et al 1999). The calculation of NIEL, requires information regarding the differential cross section for atomic displacements (dσ/dΩ), the average recoil energy of the
target atoms (T), and a term for distributing the energy into ionizing and non-ionizing events, called the Lindhard partition factor (L). NIEL can be written as an integral over solid angle, i.e.

\[
NIEL = \frac{N}{A} \int_{\theta_{\min}}^{\pi} \left( \frac{d\sigma(\theta, E)}{d\Omega} \right) T(\theta, E) L[T(\theta, E)] d\Omega
\]  

(1.3)

the integral is from \( \theta_{\min} \) to \( \pi \) and \( N \) is the Avagadro’s number, \( A \) is the atomic mass, \( \theta_{\min} \) is the scattering angle for which the recoil energy equals the threshold for atomic displacement.

NIEL can be calculated for many of particles like electron, proton, alpha particle, and heavy ions. This is due the availability of analytical forms for the differential cross sections for atomic displacement. For non-relativistic energies, simple Rutherford differential cross section can be used for elastic events. For energies where relativistic effects are important, optical model calculation can be used to account for elastic nuclear events for many positive ions. For higher energies >100 MeV for protons, nuclear inelastic contributions can be obtained using empirical data (Messenger et al 2003). NIEL for compound semiconductors, could be obtained by combining the individual NIEL contributions for the constituting atoms using the Bragg rule (i.e. via weight fractions). The effects of irradiation on the electrical parameters of many materials have been found to display a simple relationship with NIEL.

Here it will be shown how NIEL can be determined by means of the widely used computer code Stopping and Range of Ions in Matter (SRIM) (Ziegler et al 1985). A more detailed description can be found in Appendix I of (Messenger et al 1999). SRIM (Ziegler 2003) is a Monte Carlo code used
for calculations of ion penetration in a wide range of solids. Examples include semiconductors, metals, inorganic insulators, polymers and high temperature superconductors. Two data files from SRIM known as ioniz.txt and vacancy.txt contain the information necessary to derive the NIEL data. In the case of both ionization energy loss and vacancy production, SRIM divides the particle path into 100 distance intervals. The total energy loss rate is given at each interval for both the incident particle and the resultant recoils. The file ioniz.txt provides ionization energy loss rates in units of eV/Å/ion, while the file vacancy.txt provides vacancy formation information in units of the number of vacancies/Å/ion. Both files give the spatial information in units of Å. The ioniz.txt file provides a measure of particle energy at each interval while vacancy.txt provides a measure of the number of displacements. The SRIM file vacancy.txt is used in the calculation of NIEL, while both SRIM files are used in the correlation of particle depth with particle energy. The vacancy formation rate can be converted into NIEL using the modified Kinchin-Pease relationship between the number of atomic displacements, \( N_d \), and a given quantity of non ionizing energy, \( E_n \), i.e.,

\[
N_d = 0.8 \frac{E_n}{2T_d}
\]

(1.4)

where \( T_d \) is the threshold energy for atomic displacement, of the order of a few eVs. Equation (1.4) applies for \( E_n > 2.5T_d \). The number of vacancies produced by both the incident particle and the resultant recoils must be added together to obtain the total NIEL. In this way NIEL as a function of penetration depth is obtained.

In order to obtain NIEL as a function of particle energy a graph between penetration depth (µm) and NIEL (MeVcm²/g) can be first plotted. Using this graph one can obtain NIEL as function of energy. For this purpose,
the incident particle energy as a function of depth has to be determined. This can be accomplished by combining the results from the files ioniz.txt and vacancy.txt to determine the total energy lost in each of the 100 path intervals. Then a graph is drawn between penetration depth and total energy loss. Using this graph, the total cumulative energy losses is subtracted along the particle track, it is possible to establish the particle energy as a function of depth. The result of this operation is drawn as a graph which illustrates the connection between NIEL and particle energy. This will be discussed in the chapters 4 and 5 as how the use of SRIM modeling may contribute to the understanding of the results of irradiation experiments on AlGaN and GaN-based transistors. For such simulations $T_d$ of GaN was taken as 20 eV (Khanna et al 2004). In order to improve the fluctuations in the simulation large number of particle histories (99,999 histories) have been used.

1.6 GALLIUM NITRIDE FOR HFET DEVICE

With the development of the wireless communications, telecommunications, data communications and aerospace systems the demand for solid state power amplifiers has been continually increasing over the last decade. The requirements include aspects of high power level, high efficiency, high linearity and high operating frequency and the relative importance of each of these features is application specific. Many semiconductor technologies have been developed to do the power amplification. Silicon (Laterally Diffused Metal Oxide Semiconductor FET), GaAs (Pseudo-morphic High electron mobility transistor), SiGe (Heterostructure Bipolar transistor) and InP (PHEMT) are the current technologies available at the market. GaAs-based power devices have been very reliable workhorses at high frequencies especially microwave spectrum. However their power performances have been already been pushed close to the theoretical limit. In terms of power density about 1 W/mm at 10 GHz
would be the state of art performance for GaAs power pHEMTs (Gaquitré et al 1994). In the frequency range of interest, silicon devices are inherently limited by material parameters such as inversion layer mobility and saturation velocity. Silicon technology has matured to the extent that intrinsic material parameters limit the performance of devices. Figure 1.3 shows dependence of RF power on frequency for different materials.

![Diagram showing RF power vs frequency for different materials](image.png)

**Figure 1.3 Dependence of RF power on frequency for different materials**

Wide band gap technologies like SiC (Metal Semiconductor FET) and GaN (HFETs) have emerged as new technologies, which can operate at higher power levels than current technologies. GaN technology has progressed at a rapid pace and has emerged as a technology that can deliver high power at the commercially important frequency range of 2 GHz-20 GHz. This range includes most of the civilian applications like cell phone base stations, satellite communications and also military applications like phased array radars etc. To fabricate a high frequency, high power solid state amplifier, the material system must possess some basic physical characteristics. The
electron velocity and mobilities must be high, the current levels should be large and voltage levels at which the transistor can be biased must also be high. The output power then can be calculated as,

\[ P_{\text{out}} = \frac{\Delta V \Delta I}{8} \] (1.5)

where \( P_{\text{out}} \) is the output power, \( V \) is the voltage and \( I \) is the current. By maximizing both \( \Delta V \) and \( \Delta I \), which can be done by increasing the breakdown voltage and also at the same time increasing the maximum current that can be delivered by the transistor, high power performance can be improved. Gallium nitride is a material system ideally suited to do all of this.

1.7 SCOPE OF THE THESIS

Most of the studies on radiation effects have been so far conducted on Si and the most popular III-V compounds. However, recently the III-Nitride semiconducting materials have taken up an important role in opto-electronic as well as electronic sectors.

Therefore, it becomes of great actuality to investigate the defects of such compounds when submitted to irradiation with particles of different energy and nature. As device to be investigated, AlGaN/GaN Heterostructure Field Effect Transistors (HFETs) were selected and the investigation was also extended to pure thick GaN layers. In this work, the basic and technological issues associated with irradiation effects, simulating a mission of 10-100 years in space environment, will be reported. AlGaN/GaN HFET has emerged as the most promising device for microwave power amplification in satellite links and wireless communication applications.
Since one of the potential applications for HFETs is in broad-band satellite transmission for communications, television and weather forecasting systems, it is necessary that the devices be radiation resistant. As mentioned before, space radiation consists of 85% protons, 14% alpha particles and 1% heavy ions. Our standard HFET devices were irradiated with protons, carbon, oxygen with energy of 68 MeV and krypton at 120 MeV. The fluences were in the range $10^7$ to $10^{13}$ cm$^{-2}$ for different ions. The standard devices were also irradiated at low energy (2 MeV) with protons, carbon, oxygen, iron and krypton. The fluences were in the range $10^9$ to $10^{13}$ cm$^{-2}$ for the different ions. Both the energy and fluences were chosen in order to simulate the Van Allen radiation belts and 10-100 years low earth orbit mission. The AlGaN/GaN HFET devices were characterized before and after irradiation by DC characterization, pulsed I-V characterization, Hall effect, loadpull and S-parameter. The thick GaN layer was also characterized before and after irradiation by XRD, PL, Hall effect, SIMS, Raman and ellipsometry. The radiation induced effects such as the ionization and displacement damage were supported by SRIM Monte Carlo simulations for both high and low energy irradiations.