High Energy Radiation Effects in Semiconductor Devices used in Space Applications

A thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of Technology

in

Electronics and Instrumentation Engineering

by

Manik Agarwal

(Roll no. 107ei012)

Under the guidance of :

Prof. N.V.L.N Murthy

Department of Electronics and Communication Engineering
National Institute of Technology Rourkela
Rourkela-769 008, Orissa, India

National Institute of Technology Rourkela

Certificate

This is to certify that the project entitled, '**High Energy Radiation(proton, gamma) Effects in Semiconductor Devices used in Space Applications**' submitted by **Manik Agarwal** is an authentic work carried out by them under my supervision and guidance for the partial fulfilment of the requirements for the award of **Bachelor of Technology Degree** in **Electronics and Instrumentation Engineering** at **National Institute of Technology, Rourkela**.

To the best of my knowledge, the matter embodied in the project has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date - 12/5/2011
Rourkela

(Prof. N.V.L.N Murthy)
Dept. of Electronics and Communication Engineering

Acknowledgement

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Manik Agarwal

Abstract

Semiconductor is a very diverse field today. Semiconductor devices are being used everywhere these days. It holds a key for space application as well. But earths space comprises of many harmful high energy radiation. These radiations results in abnormal behavior of these semiconductor devices which is totally undesirable. In this project we study the working of some basic devices like diode and transistors. We also study the different types of radiations present in the earths atmosphere. The effect of these radiations was studied on Silicon and GaAs p-n diode and also on GaAs MESFET using ATLAS Simulation tool. Different models and methods are employed within ATLAS for our study. The parameters are set using Deep Level Transient Spectroscopy method for measuring radiation defects.

Different models such as srh, conmob, fldmob, bandgap narrowing are used for effective implementation of changes occurring related to radiation damage. Numerical methods like Newton, newton trap, Gummel, etc. are also used for calculating iteration values. We find a great deal of changes in the values of current in case of diodes. Also on studying the MESFET in presence of these radiation prone defects, we found a shift in the threshold voltage of transistor and also the performance of the device was hindered while the transistor was used as a switch, as can be inferred from the transient analysis of drain current.

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Chapter 1

Introduction

Semiconductors have a unique ability to behave as conductors as well as insulators, which depends on the energy gap between the valence and conduction bands. In case of insulators, there is a large gap between valence and conduction band whereas in conductors, the valence band overlaps with the conduction band. In case of semiconductors, this gap is somewhere in between the insulator and the conductor. Electrons can either stay in either of the valence or conduction band, and are forbid to stay in the energy gap. For this reason this energy gap is also known as forbidden gap. Electrons in the conduction band are considered to be free and participate in the flow of current. Thus, it requires some energy for the electron to move from valence band to conduction band. This energy may be of different types eg. thermal, radiation, etc.

Semiconductor material exhibit crystal defects[9] which are caused by hanging bonds or by the presence of impurities. The presence of these kinds of defects/traps changes the electrical characteristics of semiconductor devices significantly. Trap centres are those whose energy lies in the forbidden gap. It exchanges charge with the conduction and valence band through the emission and capture of electrons. Crystal Defects takes place in two possible states, empty and filled. When empty, the defect has a particular cross section for capturing an electron. When the charge on the traps centres has been changed by the addition of electrons, the defect is filled and has a new cross section for capturing of hole. We have two types of traps, donor type or acceptor type. A donor type trap can be either positive or neutral like the donor, whereas an acceptor type trap can be negative or neutral, like the acceptor.

1.1 Motivation for the project

The degradation in the performance of semiconductor devices in presence of high energy radiations due to the generation of unwanted electron-hole pair and formation of deep level traps in the crystal lattice is an area of concern for the use of these devices in space application. Research has been done on how the parameters change under the influence of radiations and how the characteristics of semiconductor devices deviates from the normal. Scientists and Researchers are coming up with new type of radiation-resistant materials which can be used in place of normal materials which are commonly used in making semiconductor devices. Progress have been made but still they have not reach to the optimum level so as to minimize the effect of these damages.

1.2 Objective of the project

The objective of the project is to study the various type of damages that effect the normal functionality of any semiconductor device. The characteristics of these devices and its parameters like current, threshold voltage in presence of radiation is also studied. The change in the value of leakage current in reverse bias condition for p-n junction using different material is also studied. The DC and transient analysis of these devices is also studied in presence of high energy radiation using ATLAS Device simulation.

1.3 Organization of the project report

This report has been organized into seven chapters.

Chapter 2

In this chapter,we discuss the work that has already been done related to the project. It gives a brief work review of related study and the progress that has been made so far.

Chapter 3

In this chapter, we discussed some basic concepts related to our project. Some basic information about diode and MESFET and their working and characteristics are discussed. Fundamentals of radiation is also been discussed which are present in the space.

Chapter 4

In this chapter,we discuss about the effect of radiation on semiconductor devices. The two type of damages occurring in presence of radiation are discussed and how they effect any device is also brought under light.

Chapter 5

In this chapter,we introduce the different types of tools that has been used for simulation purpose and for the study of various changes related to these defects. The special features of these tools have been mentioned along with their functionality.

Chapter 6

In this chapter,we present our simulation, results and analysis related to the simulation and graphs obtained. The different models used in ATLAS, the different parameters that has to be set for the study of radiation damages and the algorithm about the procedure that was followed in scripted language in DECKBUILD.

Chapter 7

In this chapter, we conclude the project and discuss the future work that can be done in this area.

Chapter 2

Related Work

In 1989, Walter L.Bloss, William E. Yamada, Mary L.Rosenbluth and Bruce K. Janousek[1] presented a paper on characteristics of GaAs DCFL MESFET'S ad inverters exposed to high-energy neutrons.Ring oscillator measurements were made to determine the effect of high-energy neutrons on the frequency performance of DCFL circuits.The results are useful in predicting how GaAs IC'c, fabricated using DCFL logic, will perform in a such environment.

In 1996, Helmuth Spieler presented a paper[3] on introduction to radiation-resistant semiconductor devices and circuits.In this paper an overview of design considerations for semiconductor radiation detectors and electronics in high radiation environments was provided.It was concluded that a judicious evaluation of the radiation fields coupled with a stringent analysis of application requirements can yield electronic systems capable of performing well to ionizing doses of 100 Mrad and particle fluences of 1014 and probably 1015 cm-2.

In 1999, Masafumi Yamaguchi, Aurangzeb Khan, Stephen J.Taylor, Koshi Ando, Tsutomu Yamaguchi, Sumio Matsuda and Takashi Aburaya[2] presented a paper on deep level analysis of radiation-induced defects in Si crystals and solar cells.Correlations between DLTS data and solar-cell properties for irradiated and annealed Si diodes and solar cells have shown that type conversion of p-Si base layer from p-type to n-type is found to be mainly caused by introduction of the 0.18 eV minority-carrier trap center.

In 2006, Becca M.Haugerd, Mustansir M.Pratapgarhwala, Jonathan P. Comeau, Akil K. Sutton, A.P. Gnana Prakash, John D.Cressler, Paul W.Marshall, Cheryl J. Marshall, Ray L. Ladbury, Monir El-Diwany, Courtney Mitchell, Leonard Rockett, Tuyet Bach, Reed Lawrence, Nadim Haddad[8] presented a paper in which the effects of proton and gamma radiations on a new SiGe technology were investigated for the first time.The effects of proton exposure on mismatch fluctutations in SiGe HBTs was also shown.

Chapter 3

Basic Concepts

3.1 p-n Diode

Diodes are the basic components for more complex devices, for example, bipolar transistors, FET and integrated circuits. A diode comprises of a p-n junction in which the p-type has majority of holes in it. While, the n-type has majority of electrons. When an external electric field is applied and the p-type side is positive with respect to the n-type, then the diode is said to be forward biased. When the polarity is reversed, the diode is said to be reverse biased. An ideal p-n diode is expected to pass all current in forward bias condition and passes nothing in case of reverse bias, thus behaving as a switch. Different types of materials are used to make p-n diodes such as silicon, gallium-arsenide, silicon-carbide, etc depending upon the application in which it is used.

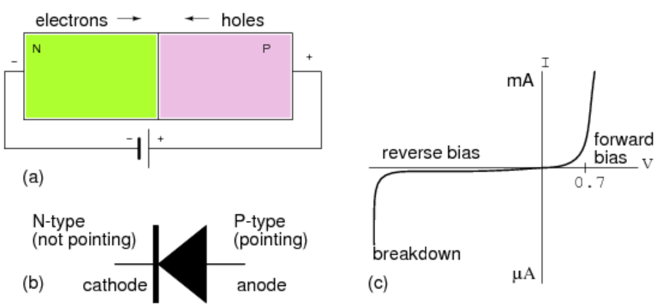

Figure 3.1: (a) Schematic of a p-n diode (b) Symbol of a p-n diode. (c) I-V characteristics in forward and reverse bias condition.

3.2 MESFET

Metal semiconductor field effect transistor differs from a simple JFET in that there is no oxide layer in case of a MESFET, rather there is a Schottky junction which is a metal-semiconductor junction. Thus, there is no insulating layer under the gate over the active switching region. MESFETS are considered to be faster than silicon based JFET and MOSFETs. These are formally used in micro-frequency communication and RADAR. Material used in case of MESFET is gallium-arsenide. The substrate used is semi-insulated for low parasitic capacitance and the active layer is deposited epitaxially. Doping is normally non-uniform and is perpendicular to the gate. This make a device which has good linearity and low noise. Gate contact is made up of titanium-platinum-gold layer, platinum itself, tungsten or aluminium. This gives high barrier height and reduces leakage current.

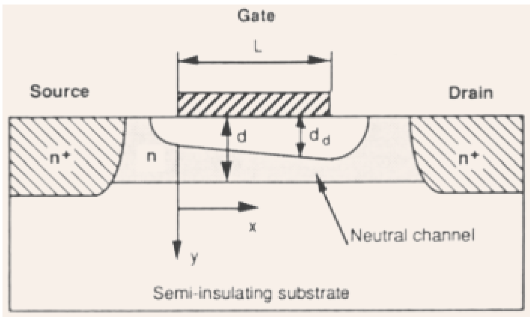

Figure 3.2: Schematic of a GaAs MESFET

3.3 Fundamentals of Radiations

Earths atmosphere is a radiation prone area which leads to defects in the semiconductor devices used in space applications. The radiation includes photons, electrons, protons, gamma rays and heavy ions. The several type of radiations are:-

1. **neutron**- it is equal to the mass of proton but has not charge.
2. **alpha particle**- they are identical to the helium atom with electric charge of +2.
3. **beta particle**- these are same as electrons with an electronic charge of -1.
4. **positron**- equal to the mass of electron and have a +1 electric charge.
5. **gamma radiation**- these are high energy radiation results from transformation

that takes place in nucleus of atom.

Radiation propagates in the form of waves or particles which has some energy which depends on the frequency of the wave. These radiations are gamma, x-rays, ultraviolet rays, visible light, infrared light, micro wave, radio wave. Since the radiation consists of massive particles which have mass, energy and charge, these particles when strike semiconductor devices leads to certain defects that are discussed in the next chapter.

Chapter 4

Radiation Defects

There are two types of radiation damage mechanisms in semiconductor devices which are described below:

4.1 Displacement Damage

In Displacement Damage, the incident radiation displaces silicon atoms from its lattice site which results in the change in electronic characteristics of a crystal. It depends on the energy and momentum transfer, which depends on mass and energy of incident quanta. Displacement damage is proportional to NIEL(Non Ionising Energy Loss)[3], which depends on particle type and energy and not on the total energy absorbed.

Displacement damage takes place in 3 important ways[3]-
1. Formation of trap level- It helps in transition of electron form valence to conduction band, which leads to an increase in the reverse biased current. In case of forward bias the trap level helps in recombination, thus leading to decrease in current i.e charge loss.
2. State that are close to the valence and conduction band capture charge and release it after a certain time.
3. It also leads to the change in donor and acceptor densities via hole emission, electron emission, electron capture, hole capture.

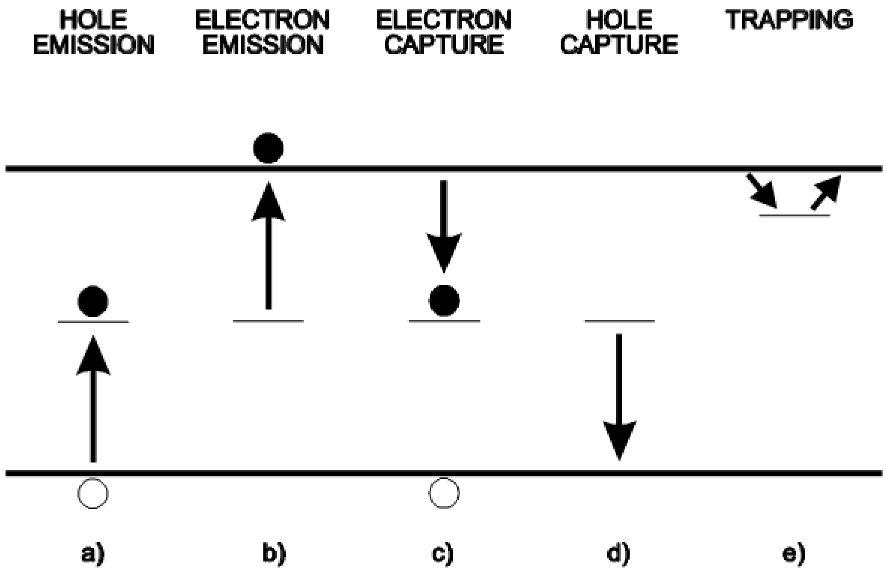

Figure 4.1: Formation of deep level traps

4.2 Ionization Damage

The energy of the radiation is absorbed in the insulating layer liberating charge carriers which then drift or diffuses leading to concentration of charge i.e. parasitic fields.
1. Ionization damage[3] leads to creation of electron-hole pair in the oxide layer. Electron being mobile in nature, moves to the more positive electrode.
2. Holes moves more slowly, which promotes probablity of getting trapped in oxide volume.
3. When positive voltage is applied to gate, electrode attracts electrons to the surface of silicon beneath the gate, leading to conduction in n-doped source and drain electrode.
4. Trapped oxide charge can also be mobile, so that charge distribution generally depends on time and also on how electric field changes with time.
5. Thus, ionization damage can be determined by interface trapped charge, oxide trapped charge, mobility of trapped charge, time and voltage dependence of charged states.

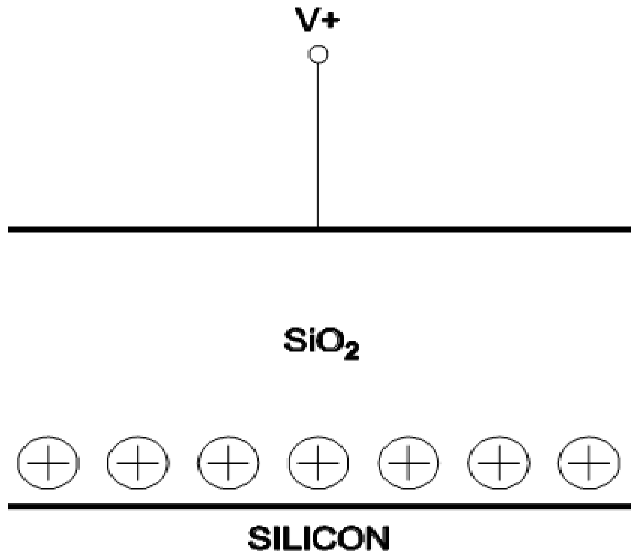

Figure 4.2: Ionization damage in Oxide layer[3]

Chapter 5

Tools Used

5.1 ATLAS Device Simulation tool

It is a 2-D or 3-D simulator to study the electrical, thermal and optical behavior of any semiconductor device. It has all the basic information about Silicon and GaAs material stored in its library. We are using ATLAS to study how the value of current changes in presence of high energy radiation in case of a Silicon p-n diode in its reverse bias condition and also the DC and Transient analysis of GaAs mesfet in presence of deep level traps that are formed in presence of these radiations.

5.2 Deckbuild

It is a graphical interface which contains powerful simulator specific statements in general script language with user defined functions. It has many standard examples stored. It also has the features of debugging the error and also specifies the error line wise in its output window.

5.3 Tonyplot

It is used for visualization of structures formed using ATHENA process simulation tool. It is also used for graphical representation of all the simulation work done using

ATLAS.

5.4 Devedit

It is a device structure editor. It is used to generate a new mesh on an existing structure, modify any device or create a device. These devices are then be used by Silvaco 2-D and 3-D simulators. DEVEDIT can be used by a Graphical User Interface (GUI) or it is used as a simulator under DECKBUILD. Before Devedit was used the mesh were poor in nature. Devedit is used to refine the mesh by setting parameters for critical areas.

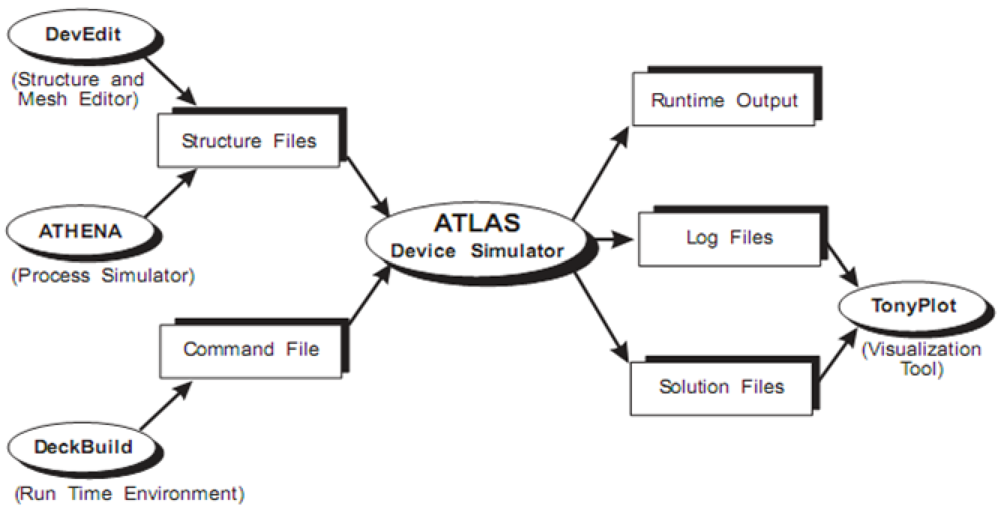

Figure 5.1: Input-Output relationship in ATLAS[9]

Chapter 6

Simulation and Result

6.1 Models Used

1. Shockley Read Hall Recombination (SRH): The transition of electron and hole becomes easier due to the formation of traps in the forbidden gap. If an Electron from these traps move to conduction band and a hole moves to the valence band, it results in creation of an electron-hole pair generation which contributes in the flow of current. This is termed as SRH generation. Inversely, if an electron moves from conduction band to these traps and a hole moves from valence band to these hole, it results in an electron-hole pair recombination termed as SRH recombination. The model depends on the energy level of these traps, the electron hole lifetime and the lattice temperature of crystal.

2. Band-Gap Narrowing: Due to heavy doping of semiconductor material, the band gap is narrowed, the conduction band is lowered as much as the valence band is raised. The model mainly depend on the concentration of intrinsic doping. ATLAS uses values from Slotboom or Klaassen as default values.

3. Concentration dependant mobility model (conmob) : This model is used to relate the field mobility to the impurity concentration at 300K. The default values for Silicon And GaAs material for mobility of electrons and hole for different values of impurity concentration is already present in ATLAS.

4. Parallel Electric Field Dependant mobility model (fldmob) : This model is again used only for Silicon or GaAs material in ATLAS. It is required to model an type of velocity saturation effect.

6.2 Parameters Used in SILVACO ATLAS

6.2.1 Displacement Damage

Figure shows the terminology used within ATLAS to define the type of trap. Trap position is defined compared to the conduction or valence bands. The level specifies the difference in energy level from valence band in case of donor traps and difference in energy level from conduction band in case of acceptor traps.

Parameters to be specified in case of traps:

1. Donor or acceptor trap.
2. The energy level.
3. Density or concentration of the trap centres.
4. The degeneracy factor.
5. The cross sections for capture of electron or hole or the electron and hole lifetimes.

Table 6.1: User Specific Parameters and their default values in case of Deep Level Trap[9]

Statement	Parameters	Units
Trap	E.LEVEL	eV
Trap	Density	per cubic cm
Trap	DEGEN	-
Trap	SIGN	cm square
Trap	SIGP	cm square

6.2.2 Ionization Damage

The capability of photo generation transient simulation is included in 3D using the SINGLE EVENT UPSET statement. Parameters[9] involved are the radial, length and time of generated charge along tracks. It can be a single particle striking or multiple strikes. Each track is has an Entry Point Location (x1, y2, z3) and an Exit

Table 6.2: User Specific Parameters and their default values in case of SEU[9]

Statement	Parameters	Default	Units
Single Event Upset	Density	0.0	per cubic cm
Single Event Upset	B.Density	0.0	per cubic cm
Single Event Upset	T0	0.0	s
Single Event Upset	Tc	0.0	s
Single Event Upset	Radius	0.05	um

Point Location (x2, y2, z2). This track traversed is considered to be a cylinder with the radius defined with the RADIUS parameter.

The electron/hole pairs generated at any point along the track is a function of the radial distance (r) from the center to the point, the distance along the track (l) and the time (t).

ATLAS defines the number of electron-hole pairs generated per cubic cm along the track according to the equation:

$$G(r,l,t) = (DENSITY*L1(l) + S*B.DENSITY*L2(l))*R(r)*T(t)$$

Where Density : number of electron-hole pair generated per cubic cm.

B.Density: number of electron-hole pair generated per cubic cm if radiation falls on it.

Parameters to be defined are:

1) Single or multiple track.

2) Entry point.

3) Exit point.

4) Density.

5) Radius.

6) B.density.

7) Delay time.

8) Characteristic time of Gaussian profile.

6.3 Simulation

6.3.1 Ioniation Damage in case of Silicon and GaAs p-n Diode

We took two p-n diodes, Silicon p-n diode and GaAs p-n diode and the transient response of current for both was studied in presence of high energy radiation using SINGLE EVENT UPSET provision provided in ATLAS.

In ATLAS we have certain parameters which are set up to study the effect of radiation such as B.DENSITY, Delay time, Characteristic time of Gaussian profile as described in the previous chapters. For this we have to specify PCUNIT parameter to initialize the study of radiation and then the other parameters values are set as per the requirement and details available.

Procedure followed for Single Event upset:

1. Devedit

1. *Work Area:* First we define the work area that is requires for the creation of any semiconductor device by defining the coordinates. The size can be altered simply by changing the values of these coordinates.

2. *Defining Regions:* The creation of any device starts by mentioning the region and the material used in those regions. The regions are defined similar to defining of the work area. The regions can also be modified. In case of overlapping area, the new region is placed and the old region is removed.

3. *Specifying material:* After defining the regions, the material is specified in each of those regions which will be filled in those regions. Most of the common element, alloys and compounds are stored in its library. New material can also be used by defining its parameters such as work function, etc.

4. *Doping concentration:* Doping type and concentration is specified in regions where doping is required. It can be uniform or Gaussian. In uniform doping the doping is uniform throughout the region, while in case of Gaussian doping, the distribution follows Gaussian distribution.

5. *Adding Electrodes:* Defining metallic contacts for applying voltage and measuring

purpose, we need electrodes which are also defined. These electrodes are defined by specifying the area, the material used, and the name of that electrode.

2. ATLAS:

1. *Defining models:* Models are defined as per the requirement and use. There are more than fifty models stored in ATLAS. These models are defined by specifying their parameters. We can even add other models in ATLAS. 2. *SEU:* Single event upset is defined by its parameters. Each parameter has its default value and should be checked before using.

3. *Simulation:* The type of response should be mentioned. The independent value should be mentioned from its starting value to end value and also the number of steps in between to define the scale of graph. The graph is obtained using TONYPLOT.

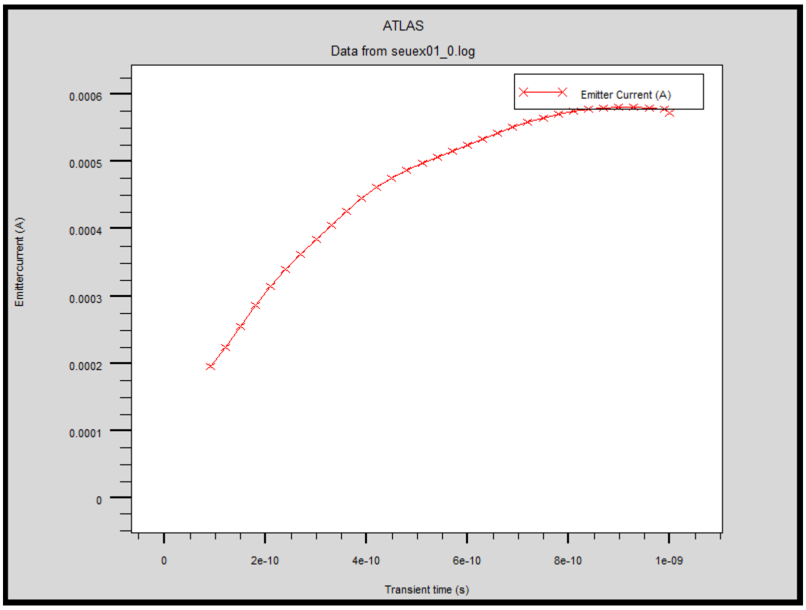

Figure 6.1: Transient Response of current for reverse bias condition in Silicon p-n diode in presence of radiation

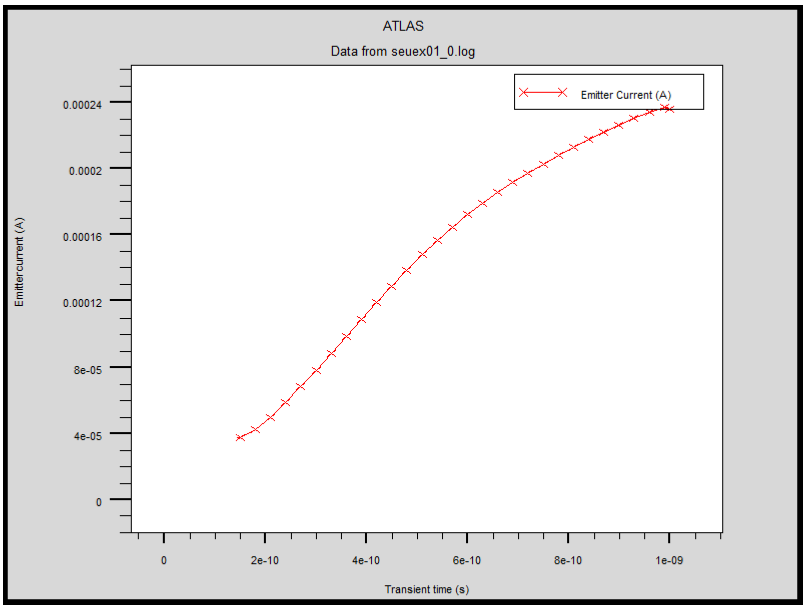

Figure 6.2: Transient Response of current for reverse bias condition in GaAs p-n diode in presence of radiation

Conclusion: From the above two simulation results , we concluded that in presence of radiation, due to the photogeneration of excess electron-hole pairs, there is some leakage current present even in reverse bas condition. For a diode to behave as a perfect switch, there should be nearly zero current, but here we find that there is some current present which increases with time to a certain value.
We also concludes that this leakage current has maximum value of 0.6 mA in case of Silicon diode while it has a maximum value of 0.24 mA in case of GaAs diode. Thus it can be seen that GaAs diode can be preferred over Silicon diode for the use in space application or radiation prone regions.

6.3.2 Displacement Damage in case of GaAs MESFET

As already mentioned Displacement damage is permanent damage that occur in a semiconductor device due to the formation of traps in the forbidden gap. These traps leads to change in the concentration of carrier ions and thus leading to change in the value of current, threshold voltage, transconductance and also hinder the performance of a transistor which is being used as a switch.
In ATLAS we mention about the energy level of these traps, the density of the traps formed, whether traps are acceptor type or donor type, the cross section area of

capturing an electron and hole, the degeneracy factor. Once these parameters are specified for a particular fluence value of any radiation coming, the DC analysis and the transient analysis was studied using TONYPLOT.

Procedure followed for Displacement damage and Deep level Traps

1. ATHENA:

1. *Defining mesh:* a 1-D mesh is defined using location of lines on x and y- axis and also specifying the spacing in between.
2. *Material used:* next we specify the material to be used within that mesh. In case of impurities, the name of impurity present along with the concentration is also mentioned.
3. *Ion implantation:* This is the main method for putting impurities in a specified region. There are many techniques being used under ion implantation, so one should chose the parameters and type carefully as per the requirement.
4. *Defining Electrodes:* Metallic contacts are defined for applying voltage and measuring purpose. The electrodes are defined by the name of material, name of electrode and the region it should occupy.

2. ATLAS:

1. *Defining models:* The different models should be specified along with their parameters that are required for a particular purpose. Many models are already stored in its library. One could introduce a new model by specifying various parameters involved in that model.
2. *Deep level traps:* Deep level traps are introduced to the semiconductor device being used. The values of different parameters such as e.level, density, sigp, sign, taun, taup, etc. values are specified. The parameters have some default values and should be specified wisely.
3. *Simulation:* The values on the x- axis, i.e the independent quantity should be specified. Its start value, the end value and the number of steps in between. The results and graphs are obtained using TONYPLOT.

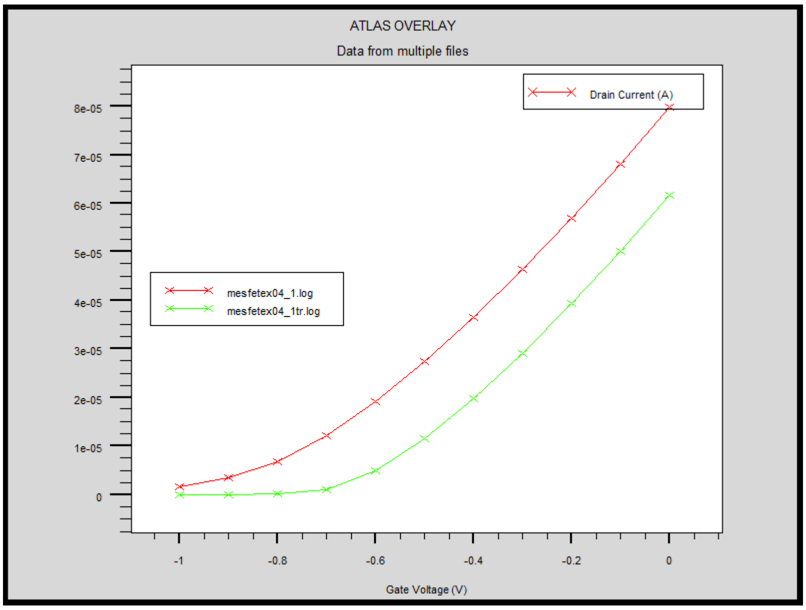

Figure 6.3: DC analysis for GaAs MESFET in presence of Deep level Traps

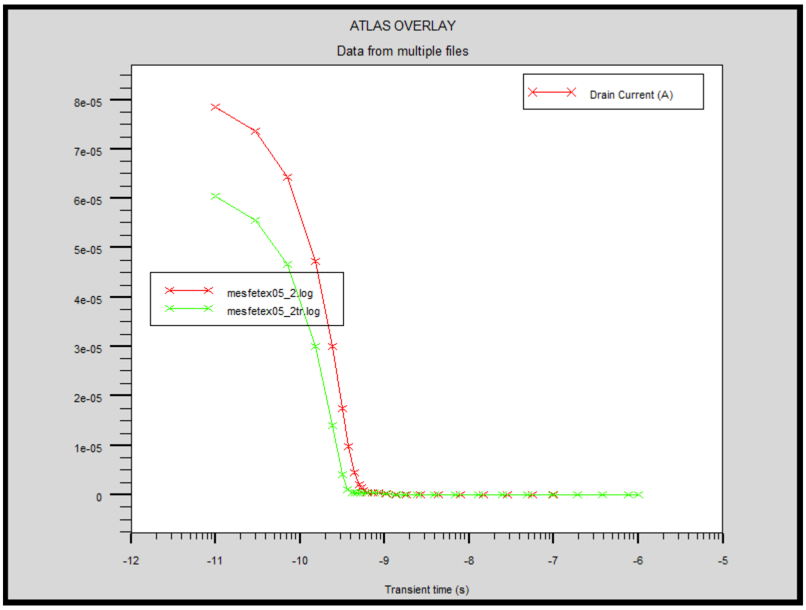

Figure 6.4: Transient Analysis for GaAs MESFET in presence of Deep Level Traps

Conclusion: The first graph is a DC analysis for the drain current in a GaAs MESFET. The red line shows the dc characteristics under normal circumstances while the green line shows the same under the influence of radiation. As can be inferred from the graph, there is a shift in the point where the value of current increases. This point is known as the threshold voltage. Thus we conclude that there is a shift in the threshold voltage to the right, i.e. the threshold voltage increases in presence of high energy radiation. The second graph shows the transient response of current when a negative gate voltage is applied. Again the red line is the response under normal condition while the green line represents the response under the presence of deep level traps created by high energy radiation. The green line takes longer time to come down to nearly zero value while the red line has a higher slope. This implies that the performance of transistor when used as a switch degrades in presence of high energy radiation.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

We have studied different types of damages existing due to the presence of high energy radiation and their effect on semiconductor devices. We have also studied the characteristics of these devices under the presence of radiation and also seen their deviation from the normal characteristics. We have used different material and the transient response for current was studied under reverse bas condition of a p-n diode. Thus we concluded that the defect is different for different material and we can rank these material according to their deviation from the normal.
We have also studied the effect of traps on GaAs MESFET. The presence of these traps increases the threshold voltage for the MESFET. This means that the gate voltage would have to be increased to get the desired output. Thus creating lot of problems in use of these devices in space application.

7.2 Future Work

The project has made progress in the field of semiconductor usage in space application but the results can be made more accurate by using DLTS method effectively. We have used the values of this method. The tool should contain the DLTS method stored in its library. Thus by conducting number of experimental trials with different values the reliability of the graph obtained can be increased. More radiation dependent models should be considered and less assumptions should be made to carry out an accurate simulation result. Factors like aging of semiconductor device should also be considered. Simulator does not take these things into account. To make results more application- specific, practical factors like aging should also be include in ATLAS.

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