Structural Characterization of Gallium Antimonide Semiconductor used in Air Space Station.

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DECLARATION

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I, Bamba Mahman, declare that the dissertation hereby submitted to the Sefako Makgatho Health Sciences University, for the degree of Master in Physics has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all material contained herein has been duly acknowledged.

[Signature]
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TABLE OF CONTENTS

Declaration i
Acknowledgements ii
Table of Contents iii
List of Symbols and abbreviations vi

Abstract 1

Chapter 1: Introduction 2
1.1 Background 2
1.2 Objectives 5
1.3 Outline of this book 5
1.4 References 5

Chapter 2: Literature Review 6
2.1 Introduction 6
2.2 Review 6
2.3 References 16

Chapter 3: Semiconductor Material 23
3.1 Introduction 23
3.2 Valence and conduction bands 23
3.3 Intrinsic semiconductor 26
3.4 Extrinsic semiconductor 26
3.5 Energy band structure 27
3.5.1 The Fermi level 28
3.5.2 Shallow and deep states 29
3.5.3 Impurities and defects 29
3.6 General properties of GaSb 30
3.7 Growth techniques 32
3.7.1 Bulk crystal growth technique 32
3.7.2 Epitaxial growth techniques 33
3.8 Application of GaSb 34
3.9 References 35
**Chapter 6: Results and Discussion**

6.1 Introduction 62
6.2 Control sample 62
6.3 Experimental samples 63
6.3.1 Annealing 63
6.3.2 Chemical etching 65
6.3.3 Argon sputtering 68
6.3.4 Oxygen gas 70
6.3.5 Electron bombardment 71
6.4 References 73

**Chapter 7: Conclusion**

7.1 Introduction 74
7.2 Chemical etching 74
7.3 Annealing process 74
7.4 Argon sputtering 75
7.5 Oxygen gas 75
7.6 Electron bombardment 75
7.7 Conclusion 75
7.8 Recommendation 76
7.9 References 76

Appendices 77
Appendix A: List of tables 77
Appendix B: List of figures 77
LIST OF SYMBOLS AND ABBREVIATIONS

AFM  Atomic Force Microscope
CMOS  Complementary Metal-Oxide Semiconductor
CRT  Cathode Ray Tube
DLTS  Deep level transient spectroscopy
DOS  Density of State
EBSD  Electron Backscattered Diffraction
EDAX  Energy Dispersive Analysis X-ray (Technique)
EDS  Energy Dispersive Spectroscopy
E  Eutectic
E + M  Etching system modified by adding 10% Magnesium oxide to increase its viscosity
EL2  Energy level 2
EPD  Epitaxial Density
FEGSEM  Field Emission Gun Scanning Electron Microscopy
EF  Fermi level
FWHM  Full Width at Half Maximum
HB  Horizontal Bridgman
HCl  Highly charged ions
HDTV  High Definition TV
HEMT  High-Electron-Mobility Transistors
IC  Integrated Circuit
LEC  Liquid Encapsulated Czochralski
ISS  International Space Station
LEED  Low Energy Electron Diffraction
LPE  Low Temperature Epitaxy
LVSEM  Low Voltage SEM
MBE  Molecular Beam Epitaxy
MCA  Multichannel Analyser
MESFET  Metal-Semiconductor Field Effect Transistors
MISSE  Materials International Space Station Experiment
MOCVD  Metal Organic Chemical Vapour Deposition
MOVPE  Metal Organic Vapour Phase Epitaxy
NASA  National Aeronautic and Space Administration
NIXSW  Normal Incidence X-ray Standing Wave
SEM  Scanning Electron Microscope
SEXAFS  Surface Extended X-ray Absorption Fine Structure
STEM  Scanning Transmission Electron Microscope
SOS  Silicon On Sapphire
STM  Scanning Tunneling Microscope
SWBXT  Synchrotron White Beam X-ray Topography
SXRD  Surface X-ray Diffraction
TEM  Transmission Electron Microscope
UHV  Ultra-High Vacuum
VPE  Vapour-Phase Epitaxy
WDS  Wavelength Dispersive Spectroscopy
XANES  X-ray Absorption Near-Edge-Structure Spectroscopy
XSW  X-ray Standing Wave
ABSTRACT

This experimental study followed the following procedure; cutting of GaSb material into samples, cleaning of samples, exposing them to various treatment conditions and analysing their surface morphologies. The n-type GaSb wafer with orientation (100) was used. Some samples were exposed to a concentration of HCl for chemical etching for different time settings, annealed, exposed to oxygen and argon fluxes and irradiated with different electron fluxes. The scanning electron microscope (SEM) was used to determine the morphological information and orientation of the samples.

The samples’ maps and images were plotted and reported for each treatment condition and compared. Bombarding the sample surface with different electrons fluxes, increased the atom mobility throughout the surface. The samples exposed to various temperatures exhibited rough surface with an increasing roughness as the temperature was increased. The etching treatment time has shown some effects on the morphology of GaSb semiconductor material. Bombarding GaSb semiconductor samples with both oxygen and argon gasses showed an increase in the size of the holes as the fluency increases.

The study has shown that an increase in particle dose caused damage or introduced defects on the surface of GaSb semiconductor material. The study recommends that the semiconductor material be treated before been used under certain conditions to improve the favorable conditions for devices on the material.

Keyword: Gallium Antomonide, Semiconductor material, Treatment Conditions, Scanning Electron Microscopy
CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Semiconductors are materials used in a variety of technologies on which human beings depend. Such technologies include laser diodes used in TV transmission, high definition TV (HDTV) development, medical and military applications. They are also used in thermoelectric coolers based on the Peltier effect to maintain a constant temperature in satellite communication and in solar panels to convert light to electricity etc… However, the harsh conditions to which they are exposed negatively affect their morphology, microstructure, electrical and electronics properties.

To solve those problems chips manufacturers have turned to radiation hardening techniques by manufacturing hardened chips on insulating substrates such as SiO$_2$ and silicon on sapphire (SOS). However, air particles like N$_2$, O$_2$, H$_2$O, CO$_2$ etc can have negative impact on semiconductor structures in general and on SiO$_2$ in particular. For example, it is reported by Winokur (2000), that one of the popular candidates for space applications is the complementary metal-oxide semiconductor (CMOS) technology due to its low power and voltage requirements. The most likely failure mechanism for CMOS resulting from total ionization dose is the loss of isolation caused by parasitic leakage paths between the source and the drain of the device (Adams 1982). However, total ionization hardness can be achieved by making changes in the isolation structure. One of the changes is to form a heavily doped region by ion implantation that effectively shuts off radiation-induced parasitic leakage paths. In addition to that, products based on semiconductor technology are still
expensive, for example solar panels that are very important source of clean energy, are not affordable.

Gallium antimonide (GaSb) semiconductor material has received increasing attention because its wavelength covers a wide range of applications which go from 1.24 µm to 4.3 µm. It has turned out to be a promising material for the application in long wavelength lasers and photodectors for fibre optical communication system.

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The semiconductor materials used in air space stations are regularly exposed to radiation particles. Cosmic rays that come from all directions are believed to be consisting of approximately 85% of protons, 14% of alpha particles, and 1% of heavy ions together with x-rays and gamma-rays radiation with energies between $10^8$ and $10^{10}$ eV (https://en.wikipedia.org/wiki/Radiation_hardening). This is a concern for spacecraft and high altitude aircraft. These particles cause lattice displacement by changing the arrangement of the atoms in the crystal lattice, creating lasting damage, and increasing the number of recombination centers and worsening the analog properties of the affected semiconductor junction. The charged particles also cause ionization effects which are usually transient, creating glitches and soft errors that can lead to destruction of the device if they trigger other damage mechanism such as photocurrent caused by ultraviolet and x-ray radiation.

Materials International Space Station Experiment (MISSE) has attached seven different experiments outside the International Space Station (ISS) to evaluate the effects of atomic oxygen, vacuum, solar radiation, micrometeorites, direct sunlight and extreme heat and cold. The results of these experiments were expected to provide a better understanding of the
durability of various materials when exposed to such an extreme environment. It is believed that many of the materials may have applications in the design of future spacecraft. Therefore more research needs to be done to improve the performance, the quality and the duration of those products and also to reduce their costs.

The purpose of this study was to analyse the surface morphology of GaSb semiconductor material after being exposed to various treatment conditions. The study has shown that an increase in particle dose cause a damage or introduce defects on the surface of GaSb semiconductor material. Some of these generated defects can improve the life span of devices fabricated on GaSb semiconductor materials while others defects can impact negatively on the properties of the material, which then affects the life span of the device. The study suggests that the semiconductor material be treated before use to improve the favorable conditions for devices.

1.2 OBJECTIVES

The objectives of this study were:

- To expose GaSb material to treatments (etching in a chemical, annealing at different temperatures, sputtering with oxygen and argon and bombarding with electrons).

- To analyze the structure of the GaSb material before being exposed to different treatments.

- To analyze the structure of the GaSb material after being exposed to the different treatments.
To compare the effects of the different treatments on the GaSb material surface.

1.3 OUTLINE OF THIS BOOK

This work is divided into chapters which are related to each other in order to meet the aspects of the objectives. The literature review on the treatment of semiconductors is discussed in chapter 2. Chapter 3 discusses semiconductor materials. Chapter 4 covers the principles of scanning electron microscopy system. Chapter 5 gives the method and procedure used in this study. Chapter 6 discusses the results obtained during the study. Chapter 7 covers the conclusion of this study.

1.4 REFERENCES


CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Gallium antimonide is a promising material for semiconductor technology application. Its structural and electronic properties are very important in the fabrication of semiconductor based device working in the energy gap of 0.3 - 2.4 eV. This chapter presents the work done on the surface morphology of semiconductor materials.

2.2 REVIEW

Hu et al (1995) studied the surface morphology of Au and Pt electroless contact on n-type ZnCdTe crystal by atomic force microscopy (AFM) and found that when the gold films were annealed in air at 300 °C for an hour there was a dramatic change in the surface morphology of the deposited gold film. They found that the grain size grew by a factor of two to three, as well as the change in surface roughness. When a similar gold film was annealed in vacuum at 300 °C for an hour, there was an increase in the mean grain diameter as well as a roughening of the surface. They noticed that new surface morphology has been formed, however, both grain and roughness did not enlarge as much as those annealed in air. In the case of PtCl₂ coated ZnCdTe crystal, they found that the one annealed in air had rougher surface than the one annealed in vacuum. They concluded that those changes are directly affecting the current-voltage (I-V) characteristics of devices.
In a similar study of the morphology and microstructure of thin-film GaAs on Mo substrates, Jones et al (1999), reported that the SEM micrographs of the surface of films deposited at 650 °C, 725 °C and 775 °C showed very rough surfaces with an increase roughness as the deposition temperature increases. They realised that many of the grains were faceted and the degree of faceting has increased significantly with the deposition temperature. They found that at 775 °C and 825 °C, the grains were seriously faceted and the surface roughness was on the order of 1 µm. The grain size increased with an increase in temperature. It has risen by a factor of 1.5 as the temperature increased from 650 °C to 775 °C.

The results obtained using SEM image of thin films grown over CdTe substrate was quite similar to the silica one. In both cases the microcrystals had triangular shape which corresponded with the (111) GaSb plane, but did not have a preferential orientation. However thin films grown over silicon and sapphire monocrystalline substrates have proved to be the most homogeneous and smooth ones. Hexagonal microcrystals of 4-5 µm have grown covering almost all the substrate in both cases. This hexagonal shape can be identified as the (111) plane of GaSb (Li et al 1999).

Woodruff (2005) reported both surface sensitivity and surface specificity were required for the determination of surface structure. Surface specificity is guaranteed by the short inelastic scattering mean-free-path for electrons in the energy range 30 eV – 300 eV, as well as the large elastic scattering cross-sections of atoms, both of which ensure that electrons which penetrate more than a few atomic layers into the solid do not contribute to the diffracted beam intensities. By measuring scattered x-ray intensity in directions that do not correspond to diffracted beams from the underlying bulk, surface structural information can be obtained from x-ray diffraction and is a particularly attractive method for the study of complex ordered
surfaces with large periodicities for which the simpler underlying theory (due to weak scattering) can have a significant advantage over low energy electron diffraction (LEED). According to Woodruff (2005), LEED and surface x-ray diffraction (SXRD) have proved extremely successful in the solution of a large number of surface structures, but they do have limitations since they cannot be used to study the important class of systems that lack long-range order. Such systems are common in molecular adsorption and co-adsorption on surfaces involving surface chemical reactions. To study those structures one needs a local structural probe such as the coherent interference of elastic electron scattering from surface atoms. Surface extended x-ray absorption fine structure (SEXAFS), a technique that exploits the same local core photoemission can be used, but the emitter atom becomes the detector.

In this case the total absorption cross section is influenced by the amplitude of the photoelectron wavefield at the emitter site which comprises a coherent sum of the directly emitted and elastically backscattered wave components. This technique is used to provide quantitative determinations of local adsorption structures. Another technique, that is used, is the normal incidence x-ray standing wave (NIXSW) which a variant of x-ray standing wave technique (XSW). In order to use this technique it must be possible to tune the x-ray wavelength, in the relatively soft x-ray energy range (down to photon energies of 2.5 keV or below or up to wavelengths of around 5 Å) necessitating the use of a synchrotron radiation rather than laboratory x-ray sources. NIXSW has several advantages such as the study of a wide range of crystals such as metal and metal oxides, with mosaicities up to tenths of degree. For surface experiments involving detection of the x-ray absorption by the associated photoelectron or Auger electron emission, the lower photon energies associated with the normal incidence condition also offer some advantages. Specifically, low photon energies
lead to lower kinetic energy electrons that are easy to detect at good spectral resolution and are more surface specific (Woodruff 2005).

In non-UHV experiments, in which the x-ray absorption is monitored by fluorescent x-ray detection, the greater absorption of the softer x-rays may prove a disadvantage.

In an experiment conducted by Jackson et al (2000), using the (111) reflection of copper with the SO2 molecule adsorbed on Cu (111), they found that the copper absorption profile was fitted by a value of a spacing 0.00 Å. The spacing giving the best fit to the S absorption profile was 0.66 Å although the true value of the spacing of the S atoms relative to the outermost Cu layer is one bulk interlayer spacing (2.08 Å) larger than this at 2.74 Å. According to Woodruff (2005) this result highlights the fact that the XSW technique provides a measure of the absorber atom location relative to the nearest extended substrate scattered plane, and not relative to the nearest actual substrate atomic plane.

In a study conducted by Zhuang and Edgar (2005), Ga-polar GaN epitaxial films (0001) were selectively attacked and showed hexagonal etch pits after etching in hot phosphoric acid. The N-GaN films etch quickly; with either complete film removal or a drastic change in surface morphology while only hexagonal etch pits associated with defect formed on Ga-polar films, leaving the defect free GaN areas intact and the morphology unchanged. Similarly, Shimizu et al (1998) noticed severe morphology degradation for presumably N-polar molecular beam epitaxy (MBE) grown in GaN etched in phosphoric acid at temperatures higher than 220 °C. Many experiments are in agreement with the fact that the N-polar GaN etches more readily than the Ga-polar GaN. Morimoto (1974) and Shintani and Minagawa (1976) reported a similar etch rate, about 1 μm/min, for metal organic chemical vapour deposition (MOCVD) grown GaN etched in phosphoric acid at temperature around 200 °C. They concluded that
etching produced hexagonal etch pits reflecting the crystal symmetry of GaN. Kim et al (1998) reported the same shape etch pits after etching in phosphoric acid at a temperature around 215 °C. No significant etching was observed at 160 °C and below. The etch pits shape and size cannot be associated with a specific defect. The origin of the hexagonal etch pits was disputed. For Hong et al (1998) who studied the same sample as Kim et al (1998), argued that those hexagonal etch pits are formed on the micropipes, i.e. open core screw dislocations, but not on the threading dislocations.

According to Zhuang and Edgar (2005) several studies found that the etch pits varied in size and the epitaxial density (EPD) was generally lower than the dislocation density evaluated by transmission electron microscope (TEM). Kozawa et al (1996) ascribed the etch pits formed in GaN by molten KOH etching to dislocations, though the epitaxial density (EPD) (2 \times 10^7 \text{ cm}^{-2}) was one order of magnitude lower than that measured by TEM (2 \times 10^8 \text{ cm}^{-2}). Ono et al (1998) reported a reduction of EPD from 4 \times 10^7 to 6 \times 10^6 \text{ cm}^{-2} by inserting a thin buffer layer of InGaN. However according to TEM measurement the dislocation density remained 10^9 \text{ cm}^{-2}. Zhuang (2005) reported that in many respect the wet etch of AlN and GaN were quite similar such as a higher etch rate for N-polar crystals, the shape of etch pits, and the slow-etch crystal planes that developed during anisotropic etching.

The one significant difference they have noted was that, even high quality N-polar AlN could be etched in aqueous solutions near room temperature but GaN could not. Another difference is the higher dislocation density in epitaxial layers compared to GaN layers. Differences in the etching behaviour due to the crystal polarity were reported by Jasinsky et al. (2003) for an AlN epitaxial layer grown on sapphire substrate. The etch rate of the Al-polar crystal was much slower than that of the N-polarity crystal in 50 % aqueous KOH solutions at 80 °C.
According to Schowalter et al (2000), the investigation of crystals having lower defect density, such as bulk AlN single crystal grown by sublimation-recombination technique, has revealed that they were more resistant to etching than AlN epitaxial layers. They also reported different etching behaviour for the two sides of a vicinal c-face AlN substrate (cut 20° off axis). They found that a phosphoric acid/sulphuric acid mixed produced a rough surface morphology on the nitrogen face, but did not etch the Aluminium face. When a ratio of 1:2.5 KOH:water was used in place of the acid they found that the same etching results was obtained. However the etch rate was slower than in phosphoric acid. After etching, AFM revealed that the nitrogen polarity surface consisted of pyramids 0.5-1.5 μm high. Similar results were reported by Zhuang et al (2002) for bulk AlN, the nitrogen polarity (0 0 0 1) basal plane initially etched rapidly, while the aluminium polarity basal plane and prismatic (1 1 0 1) were not etched.

The etch rate of the nitrogen basal plane decreased to zero, as the surface became completely covered with hexagonal hillocks, presumably bounded by {1 1 0 1} planes. Such planes are chemically stable according to Zhuang et al (2002), due to the smaller number of bonds through these planes compare to other planes families. Zhuang et al (2002) reported that, because of the identical crystal structure of wurtzite GaN and AlN, the planes limiting the pyramids formed on N-polar GaN surface reported in Hock et al (2003a), (2003b) and (2003c) and the hillocks formed on N-polar AlN had the same orientation (the {1 1 1 0} and {1 0 0 1}) which belonged to the same family. They noticed that neither the hexagonal pyramids formed on N-polar GaN nor those formed on N-polar AlN are associated with the structural defects.
According to Weyher et al. (2000) and Kamler et al. (2002) the optimal etching temperatures are polarity dependent in eutectic \((E)\). They found that the best temperatures were 350 – 450 °C and 200 - 250 °C for Ga-polar and N-polar surface respectively. They found that the appropriate etching time depended on defect density/type and is in the range of 1-5 min; long times were needed for lower density materials. They noticed that etching produced hexagonal etch pits on Ga-polar and circular etch pits on N-polar surface respectively. They attributed the hexagonal etch pits on the Ga-polar to the crystallographic symmetry of the GaN lattice. They used TEM measurement, and it has confirmed that the etch pits were formed on dislocations. Using SEM image of etching pattern produced in Eutectic \((E)\) and Etching system modified by adding 10% Magnesium oxide to increase its viscosity \((E + M)\) for Al-polar AlN epitaxial film Zhuang et al. (2002) observed the presence of a linear array of hexagonal pits.

They concluded that those defects belonged to the same grain. They have also observed the presence of randomly distributed pits. All hexagonal pits had the same orientation and were almost the same size. When a bulk Al-polar AlN was grown by directly heating the source materials by microwaves they got an EPD which is about \(6 \times 10^6 \text{ cm}^{-2}\) and it was in agreement with the dislocation density \((6 \times 10^6 \text{ cm}^{-2})\), which is determined using synchrotron white beam x-ray topography (SWBXT). They concluded that the etch pits on Al-polar surface did form on dislocations. However they could not find the correct explanation as why GaN and AlN which have identical structures (wurtzite), when etching in \(E\) produced hexagonal hillocks on N-polar AlN and rounded pits on N-polar GaN.

A study conducted by Jiang, et al (1998) on the dependence of surface morphology of doped GaAs on the crystallographic orientation show that those elements with smaller atomic weight have a larger impact on the surface morphology than other dopants. Among many
other dopants that have been studied, Mg (magnesium) and O\textsubscript{2} (oxygen) shown to have a greater effect on the formation of the surface structure. The presence of O\textsubscript{2} particularly at the steps edges cause the gradual roughening of the surface. The height of the roughness of epitaxial layers decreases considerably compared to samples with an increase of Sb concentration in the GaAs layers.

These effects of atomic interlayer are attributed to interface dipoles (Jing et al 1995). Grugel et al (2013) reported that when defects are trapped in solid samples, they show up internal cracks that diminish a material’s strength and usefulness.

Chiodoni (2005) has grown CeO\textsubscript{2} on Si under different conditions by means of a sputtering system. The first sputtering sample namely A was using the ratio of Ar:O\textsubscript{2} (39:1) mixture. They found that the x-ray diffraction patterns exhibits a preferential orientation in the (111) direction, inferred by the \(\theta-2\theta\) characterisation, and a flat surface laced by pyramidal-shaped crystals whose vertical size was about 90 nm. They attributed the presence of the peaks to the growth of a fraction of crystallites randomly oriented and to asymmetric spurious contributions of some crystallites with slight tilt to the c-axis. AFM image of the sample has shown a flat matrix over which there were some pyramidal-shaped crystals whose vertical size was about 90 nm, confirming the result of the x-ray.

Furthermore TEM analysis has revealed the presence of a columnar preferential growth and shows the presence of an amorphous layer of about 2 nm at the Si/CeO\textsubscript{2} interface. They attributed the non-epitaxial growth of the CeO\textsubscript{2} film to the presence of the amorphous layer. In the second sample (sample B) pure Ar was used in the absence of oxygen in the chamber. The results she obtained were similar to the one in sample A in many respect. However there was no reflection in the thin film spectrum with respect to the corresponding of sample A.
This has led to the argument that sample B exhibited a better structural quality than sample A. And the full width at half maximum (FWHM) of 5.5° points was reported as an out-of-plane angular spread in this direction. They observed that the film showed no specific order in plane direction, but it was fibre textured. They concluded that in the absence of oxygen in the plasma, CeO₂ grows in a reproducible way as a well textured, rather flat, near stoichiometric group of crystallites, (111) oriented, with the [111] direction laying in a quite narrow range (5.5°) near the normal to the surface.

According to Lang et al (2009), Navitski et al (2009), Akcoltekin et al (2007) and Cornelius et al (2005) swift heavy ions (MeV-GeV kinetic energy) have become an important tool for structural modifications of various materials at the microscale and nanoscale for a wide range of applications in recent years. They reported that such heavy ions can however have a negative impact in some applications if they damage the deep layers. El-Said et al (2007a) and Schwartz et al (2004) reported that electronic energy loss was the major cause of material modification whereas Aumayr et al (2004) reported that potential energy deposition was dominating surface modification by highly charged ions (HCI). El-Said et al (2007b), (2008) and Terada (2005) reported that HCI had induced surface modifications such as hillocks, Tona (2007a) demonstrated the presence of craters, Heller et al (2008) had shown the existence of pits after using HCI as etchant and Tona (2007b) had found calderalike structures with nanometre dimensions. El-Said et al (2010) reported triangle-shaped pits of BaF₂ samples etched after irradiating with (4.5q × kV) Xe^{24+}, Xe^{26+}, Xe^{33+} respectively.

The sizes of the pits increased with the incident charge state and also the number of the pits increased as the ion fluency increased. Furthermore, nanostructures in the form of pyramidal pits have been observed for Xe-ion state (q = 36) in the BaF₂ (111) after chemical etching.
Those observations were extended to KBr (001) and CaF$_2$ (111). In all cases the nanostructure can be associated to individual ion impact events and the size of the generated nanostructures depends on the charge state and therefore on the potential energy deposited by the HCI into the surface.

According to Moustakas (1982) electronic bombardment of a sample did not always have undesirable effects in the growth of semiconductor material. They found that some electronic bombardments could have a favourable effect on the structurally and compositionally homogeneous sputtered of Si-H films. They found that under typically sputtering conditions, there are low-energy and high-energy electrons arriving at the substrate. Bombardment by these electrons could have profound effects on the films chemistry and structure because it enhanced an atom surface mobility through surface heating. Moustakas (1982) believed that electron bombardment was responsible for the perfect coalescence of the island structure, which led to films having both structural and compositional homogeneity.

El-Said et al. (2007a), El-Said et al. (2008) and Heller et al. (2008) reported that nanostructures in the form of pyramidal pits could be revealed after chemical etching CaF$_2$, BaF$_2$ and KBr. Those nanostructures could be unambiguously associated to individual ion impact events. They found that the size of the generated nanostructures strongly depended on the charge state and therefore on the potential energy deposited by the HCI into the surface. According to them, the potential energy played a decisive role in the formation of nanostructures. They explained this by taking into consideration the fact that damage creation in ion-surface collisions was strongly correlated with the form of energy deposition in the solid.
This energy transfer to target cores led to atomic displacements and lattice vibrations in the target (phonons). In another study Aumayr et al. (2008), Aumayr et al. (2004) and Schenkel et al. (1999) reported that slow heavy charged ions transfer their potential energy via a series of Auger processes to the electronic subsystem of the target. For Arnau et al. (1997) and Aumayr (2007) the results of the Auger processes were: (1) a large number of electrons emitted from the projectile into a shallow region close to the HCI zone, (2) Aumayr et al. (2004) and (2008) and Facsko et al. (2009) reported that an inelastic interaction of these electrons with target atoms led to a strong electronic excitation of a nanometer-sized region around the impact site, i.e., generation of defects such as excitons, color centers, holes etc., and production of further (secondary) electrons, and (3) elastic collisions of these electrons with target atoms (electron-phonon coupling) heat the lattice in the surrounding of the impact site. Using modelling calculations for HCI impact on CaF$_2$, El-Said et al. (2008) and Lemell et al. (2007) have shown that above a certain energy threshold, the heating of the lattice atoms by these primary and secondary electrons could surpass the melting threshold of the solid. Heat and pressure deformed the surface and after cooling down a hillock remained at the surface.

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CHAPTER 3
SEMICONDUCTOR MATERIAL

3.1 INTRODUCTION

Semiconductors are material with electrical conductivity intermediate between metals and insulators. This conductivity can be varied by varying temperature, impurity content or by optical excitation (Ohring 2002). To be able to electrically characterize semiconductor materials, an understanding of their basic properties is needed. Electrical conduction in a semiconductor material is facilitated by the movement of carriers in occupied states (electrons in the conduction band or holes in the valance band). The concentration of these electrons and holes can be controlled by the amount of impurities, which are purposely introduced into a semiconductor. Semiconductors are distinguished from other materials by the fact that their atoms are held together by strong directional covalent bonds between nearest neighbouring atoms.

3.2 VALENCE AND CONDUCTION BANDS

Every solid contains electrons. For the electrical characterization of semiconductor it is, amongst others, necessary to know the response of electrons to an applied electric field. For an intrinsic semiconductor there are just enough electrons to fill all the states in the valence band. The conduction band contains most of the excited electrons from the valence band. To obtain a semiconductor material that is useful for device fabrication, it is necessary to dope the material with specific impurity atoms (Dhanse karan et al 2000). In general adding group V element atoms results in extra electrons within the semiconductor yielding an n-type semiconductor material. Similarly, adding group III elements, only three covalent bonds are
complete; resulting in holes producing a p-type semiconductor material for group IV. The irradiation of semiconductors introduces defects with energy levels in the forbidden band-gap. These defects capture some of the free carriers and thereby change the electrical properties of the semiconductor devices.

The total number of electrons in the conduction band of the semiconductor is given by:

$$n = \int_{E_C}^{E_{\text{top}}} N(E)F(E)dE$$  \hspace{1cm} (3.1)$$

where $N(E)$ is the density of states in the conduction band and $F(E)$ is the probability that a given state is occupied. $E_{\text{top}}$ is the energy at the top of the conduction band and $E_C$ is the energy at the bottom of the conduction band (Sze 1981). The probability that a state is occupied is given by the Fermi Dirac distribution function:

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$  \hspace{1cm} (3.2)$$

where $k$ is Boltzmann's constant, $T$ is the absolute temperature, and $E_F$ is the Fermi energy. The density of states in the conduction band can be approximated by

$$N(E) = M_C \frac{\sqrt{2}}{\pi^2} \frac{(E - E_C)^\frac{3}{2}}{\hbar^3} \left(m_{de}\right)^\frac{3}{2}$$  \hspace{1cm} (3.3)$$

where $M_C$ is the number of equivalent minima in the conduction band, $\hbar$ is the reduced Plank's constant and $m_{de}$ is the geometric mean of the effective masses along the principal axes of the ellipsoidal energy surface. Using equation (3.2) and (3.3) and evaluating the integral in equation (3.1) gives:
\[ n = N_C \frac{2}{\sqrt{\pi}} F_{\beta} \left( \frac{E_F - E_C}{kT} \right) \]  

(3.4)

where \( N_C \) is the effective density of states in the conduction band and \( F_{\beta} \) is half of the fermi level. \( N_C \) is defined by

\[ N_C = 2 \left( \frac{2\pi m_d kT}{\hbar^2} \right)^{\frac{3}{2}} M_C \]  

(3.5)

For the Boltzmann statistics case, i.e. for the Fermi energy several \( kT \) below \( E_C \) in nondegenerate semiconductors, equation (3.4) becomes

\[ n = N_C \exp \left( - \frac{E_C - E_F}{kT} \right) \]  

(3.6)

By similar argument the concentration of holes in the valence band is found to be

\[ p = N_v \frac{2}{\sqrt{\pi}} F_{\beta} \left( \frac{E_V - E_F}{kT} \right) \]  

(3.7)

where \( N_v \) is the effective density of states in the valence band given by:

\[ N_v = 2 \left( \frac{2\pi m_d kT}{\hbar^2} \right)^{\frac{3}{2}} \]  

(3.8)

and \( m_{dh} \) is the density of state effective mass of the valence band given by:

\[ m_{dh} = \left( m_{lh} \frac{3}{2} + m_{hh} \frac{3}{2} \right)^{\frac{2}{3}} \]  

(3.9)

where \( m_{lh} \) and \( m_{hh} \) refer to the "light" and "heavy" holes respectively. It follows that:
\[ p = N_v \exp\left( -\frac{E_p - E_V}{kT} \right) \] (3.10)

3.3 INTRINSIC SEMICONDUCTOR

A perfect crystal structure which contains no chemical impurities and in which no atoms are displaced from their lattice sites is called an intrinsic semiconductor. In such material, there are no charge carriers at 0 K since the valence band is filled with electrons and the conduction band is empty of electrons. At higher temperatures, electrons are excited thermally across the band gap to the conduction band. Each electron, which is excited into the conduction band, leaves a hole in the valence band; therefore the number of electrons and holes should be equal.

3.4 EXTRINSIC SEMICONDUCTOR

When a crystal is doped such that the equilibrium carrier concentration of electrons and holes are different from the intrinsic carrier concentration, the material is said to be extrinsic. It is possible to create carriers in semiconductors by introducing impurities into the crystal so that it has a predominance of either electrons or holes. When impurities are introduced into a perfect crystal, additional levels are created within the energy band. An energy level introduced by an impurity near the conduction band is called a donor level and an energy level introduced near the valence band is called an acceptor level.
3.5 ENERGY BAND STRUCTURE

Ever since the application of the band theory of metals to semiconductors, this theory has been successful in explaining the properties of semiconductors. The most important result of the application of quantum mechanics to the description of electrons in a solid is that the allowed energy levels of electrons and holes are grouped into bands (Neamen 2006). The lowest energy band or valance band ($E_v$) is completely filled with electrons because of the Pauli exclusion principle. At zero temperature, the upper energy band is normally empty of electrons, because it consists of the unoccupied higher levels in the isolated atom.

The energy region between these two bands is called the forbidden energy gap or so-called band-gap, since no energy levels within the band-gap may exist in a perfect crystal. For example electrons in n-type material, which have been promoted to the conduction band ($E_c$) by the addition of energy from some source, can conduct electricity. The size of the band-gap determines the amount of energy required for this transition. Therefore, depending on the size of this band-gap, a material can be classified as an insulator or semiconductor.

With the aid of optical transmission experiments on semiconductors, a number of workers concluded that semiconductors can further be classified as direct or indirect-gap materials (Neamen 2006). Values for the energy gap as well as some other general properties of most common semiconductors are indicated in table 3.1.
Table 3.1 Properties of some commonly used semiconductor materials (Sze 1981)

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Crystal structure</th>
<th>Eg (eV)</th>
<th>Bandgap Type</th>
<th>Melting Point °C</th>
<th>Hall Mobility (cm²/V.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 K</td>
<td>300 K</td>
<td></td>
<td>Electron</td>
</tr>
<tr>
<td>GaAs</td>
<td>Cub.Z.B</td>
<td>1.52</td>
<td>1.42</td>
<td>Direct</td>
<td>1238</td>
</tr>
<tr>
<td>Ge</td>
<td>f.c.c</td>
<td>0.74</td>
<td>0.66</td>
<td>Indirect</td>
<td>937</td>
</tr>
<tr>
<td>Si</td>
<td>f.c.c</td>
<td>1.17</td>
<td>1.12</td>
<td>Indirect</td>
<td>1415</td>
</tr>
<tr>
<td>GaSb</td>
<td>Cub.Z.B</td>
<td>0.81</td>
<td>0.72</td>
<td>Direct</td>
<td>712</td>
</tr>
<tr>
<td>GaP</td>
<td>Cub.Z.B</td>
<td>2.34</td>
<td>2.26</td>
<td>Indirect</td>
<td>1460</td>
</tr>
<tr>
<td>AlSb</td>
<td>Cub.Z.B</td>
<td>1.68</td>
<td>1.58</td>
<td>Direct</td>
<td>1065</td>
</tr>
</tbody>
</table>

3.5.1 THE FERMI LEVEL

The Fermi energy levels for an intrinsic semiconductor lie very close to the middle of the band-gap. When impurity atoms are introduced, the Fermi level must adjust itself to preserve charge neutrality. For an intrinsic semiconductor the number of electrons in the conduction band is equal to the number of holes in the valence band. The Fermi level for an intrinsic semiconductor is obtained by equating equations (3.6) and (3.10):

\[
E_f = \frac{E_c}{2} + kT \ln \left( \frac{m_p}{m_n} \right) \tag{3.11}
\]
3.5.2 SHALLOW AND DEEP STATES

Shallow states are located near the valence band as acceptor states and near the conduction band as donor states.

Deep states are classified as those, which are positioned deeper than the shallow level in the band-gap. Deep states tend to be non-radiative recombination centres. Several techniques including capacitance based techniques provide opportunities for the electrical characterisation of these states.

3.5.3 IMPURITIES AND DEFECTS

The influence of small amounts of impurities present in a semiconductor can drastically influence its electronic properties. This phenomenon forms the basis of semiconductor technology. There are two types of impurities in semiconductors. Firstly, those which are responsible for the conduction and which have shallow energy levels, Low, energy levels within the band gap close to the conduction or valence band. These are referred to as dopant impurities (Myers 1997).

Dopant atoms from elements in a column of the periodic table to the right of the host atom are in general referred to as donors because they have more unpaired valence electrons than the host atoms and give rise to n-type semiconductors. Those to the left are called acceptors because they can accept electron from the host atoms in order to fulfil local bonding requirements and lead to p-type semiconductor.
The second type of impurity has energy levels, which lie further from the band edges, and usually referred to as deep defects states, traps, recombination centres, generation centres, deep levels or deep impurities. In a neutral semiconductor material, an electron trap is defined to be a defect for which the electron capture is larger than the hole capture rate. In contrast, a recombination centre is defined as a defect for which both the electron and hole capture rates are large and comparable in magnitude.

The defects which are localised with atomic dimension are called vacancies (vacant atomic site) and interstitial (extra atom occupying an interstitial site). A Frenkel defect is in principle formed by removing an atom from its lattice site and then placing it in an interstitial position, thus forming a vacancy-interstitial pair. This defect may play an important role in the formation of other defects (Kittel 1996).

3.6 GENERAL PROPERTIES OF GaSb

GaSb is formed when Ga element of group III and Sb of group V are combined. It is one of the members of the family of III-V compounds. It is a direct band-gap semiconductor with a smaller effective mass than an indirect band-gap material such as Si. This property provides the electrons in GaSb with a very high mobility, which makes it one of the most important materials for the fabrication of optoelectronic devices. Typical electron mobility values of 8000 cm²/V.s and higher for GaSb are obtained, five times faster than that of Si (1500 cm²/V.s), see table 3.1. These mobilities for GaSb increases with a decrease in temperature down to 10 K or if multi-layer supperlattices are grown such as in metal-semiconductor field-effect transistors (MESFET’s).
GaSb is one of the most commonly used materials for fabricating semiconductor devices. Being a compound III-V semiconductor, GaSb has an ionic bonding between Ga and Sb. Consequently, the nature and reactivity of a GaSb surface depends on its orientation, and therefore, the new defects are known to play an important role in the electronic properties of the semiconductor.

**Figure 3.1**: The (atomic) crystal structure of GaSb. (http://www.webelements.com/compounds/gallium/gallium_antimonide.html)
3.7 GROWTH TECHNIQUES OF GaSb

The performance and suitability of semiconductor devices critically depends on the state of perfection of the different growth techniques, because the formation of process-induced defects is often closely related to the defect structure present in the as-grown bulk material. GaSb, compared to Si, the crystal growth is more sensitive to thermal gradients and temperature changes during the growth process. These changes normally generate crystal dislocations and other structural defects (Wasa et al 2004).

3.7.1 BULK CRYSTAL GROWTH TECHNIQUE

The three most popular methods for bulk growth of GaSb are the:

i) Liquid Encapsulated Czochralski (LEC)
ii) Horizontal Bridgman (HB) or gradient freeze
iii) Czochralski pulling technique

Apart from the fact that their orientations may differ, the crystals grown by these techniques have significantly different defects and impurity densities, and therefore electrical properties. One of the major problems related to these high temperature growth techniques, is the Si contamination which originates from the reactor materials. Depending on the growth conditions, Si can act either as a donor or acceptor and can affect the electrical behavior of the substrate (Mohan et al 1996). In the HB process the Si contamination has been suppressed by the deliberate addition of dopants such as O₂, which results in high resistivity GaSb. The HB grown crystals further have lower defect densities than LEC crystals.
3.7.2 EPITAXIAL GROWTH TECHNIQUES

The semiconductor device technology of the future demands the fabrication of multi-layered solid-state structures with low defect and impurity concentration. This may be achieved by using one of the following epitaxial growth procedures.

Major epitaxial techniques are:

i) Liquid-phase epitaxy (LPE)

ii) Vapor-phase epitaxy (VPE)

iii) Molecular beam epitaxy (MBE)

iv) Metalorganic chemical vapour deposition (MOCVD)

All of these methods have received considerable attention in the past (Wasa et al 2004, Serikawa et al 2005, Mohan et al 1996).

MOCVD has become a very attractive technique for the growth of sophisticated multilayer structures of compound semiconductors. The mobilities of MOCVD grown GaSb are limited by electrical compensation resulting from impurities in both the metal alkyl and hydride sources. With the aid of deep level transient spectroscopy (DLTS) it was established that the MOCVD layers have deep level impurities that are controlled by the particular source material, while photoluminescence studies have shown that the primary residual shallow acceptors present were Zn and C. This method also introduces the energy level 2 (EL2) defect.
The major disadvantage of LPE is that the surface morphology of the grown layers is inferior to that produced by MBE or VPE and so it introduces difficulties in the subsequent processing of devices. Another is the restricted substrate size that can be used in the sliding boat systems to maintain acceptable uniformity. However, LPE can produce high electrical and optical quality GaSb (Wasa et al 2004, Serikawa et al 2005, Mohan et al 1996).

3.8 APPLICATION OF GaSb

Metallisation of GaSb has received wide-spread attention in technology, because of its important applications in integrated circuits and infrared detection. GaSb is used in a number of different types of devices (Subkti et al 1999).

An application includes photonic and electronic devices. The photonic devices could be divided into three basic groups: (i) the devices that convert electrical energy into optical radiation e.g. LED's and laser diodes, (ii) devices that detect optical signals through electronic processes e.g. photodetectors, and (iii) devices that convert optical radiation into electrical energy e.g. photovoltaic devices or solar cells (Subkti et al 1999).

Gallium antimonide is an important material in field-effect transistors, heterojunction bipolar transistors, solar cells and integrated circuits and these components are becoming increasingly important in space applications. GaSb offers a wider range of operating temperatures and much higher radiation hardness than Si. Integrated circuits fabricated from GaSb by standard processes can withstand temperature from -200 to +200 °C while operation up to 400°C may be possible with special processes (Dutta et al 1995).
Gallium antimonide is an important material for devices to be used in space applications, because of its resistance to radiation damage (Dutta et al 1995).

A number of GaSb semiconductor devices manufactured today must ultimately function in an environment fraught with radiation hazards. The applications of Schottky barrier diode include rectifiers, microwave switches, and mixer circuits, as well as level shifting and electrostatic discharge protection circuits.

It has also emerged as an optoelectronic material in the early 1960s. Applications of these devices include optical communication between satellites, telecommunication systems and thermal printing systems. High electron mobility transistors (HEMTs) have improved gain and noise performance over an extended frequency range. A further advantage of a HEMT is that it can be incorporated into either monolithic or hybrid microwave and millimeter-wave IC's for space application (Subkti et al 1999).

3.9 REFERENCES


Gallium: Gallium Antimonide

Material international space experiment.
https://www.google.co.za/?gfe_rd=cr&ei=32SqVs-bD-yo8we8-Y2ACg&gws_rd=ssl#q=material+international+space+station+experiment+(misse)


CHAPTER 4

SCANNING ELECTRON MICROSCOPY SYSTEM

4.1 INTRODUCTION AND HISTORY

An electron microscope (EM) is an instrument that uses a beam of energetic electrons to produce images of objects. It has a very high resolution and can resolve objects on a very small scale. Before the development of the EM, several attempts have been made to design instruments that can magnify small objects. By the 16\textsuperscript{th} century, the microscope used by scientists did not magnify well. However, during the 17\textsuperscript{th} century they improved the magnification as well as the strength of the lenses (Rochow 1994).

In 1590, Hans Janssen and his son (Zaccharias) developed the compound microscope which is still used today. Robert Hooke improved on Janssen’s compound microscope. In 1674 Anton van Leeuwenhoek built microscope capable of magnifying objects 270 times. His microscope could observe micro-organism such as bacteria (Rochow 1994).

An improvement of the magnification of the microscope has bee achieved with the invention of the transmission electron microscope (TEM) by the German scientist, Ernst Ruska in 1933. The TEM can magnify objects millions of times. In 1981 Gerd Bining and Heinrich Rohrer invented the scanning electron microscope (SEM) (https://en.wikipedia.org/wiki/Ernst_Ruska).
We will focus our attention on the SEM used in this work. It is a large, expensive piece of equipment which is generally standing alone in a small designed room. Figure 4.1 shows a picture of SEM system.

![SEM System](image)

**Figure 4.1** Picture of Scanning electron microscopy

### 4.2 MAJOR COMPONENTS

The SEM is made up of two basic systems with the sample at their boundary. The first system is the electron optical column which provides the beam of electrons that is directed to the specimen. The second system consists of the electron collection, signal amplification, and image display units which convert the electrons emitted from the specimen into a visible image of the sample.
4.2.1 ELECTRON GUN

According to Wischinitzer (1998), the SEM has an electron gun that produces a stream of monochromatic electrons. There are different types of electron guns such as the tungsten filament cathode, the lanthanum hexaboride (LaB6) cathode and the field emission gun. The electrons are emitted from thermionic source such as a filament or cathode. They are accelerated by a field between the cathode and the anode. The potential difference between cathode and anode is about 15 kV. The emission current density is given by the Richardson’s equation.

\[
I_0 = AT^2 \exp\left(-\frac{eW}{k_B T}\right)
\]

(4.1)

where \(I_0\) is the emission current density (amps per cm²), \(A\) is a constant which is a function of the material, \(e\) is the charge of the electron, \(W\) is the work function, \(k_B\) is the Boltzmann’s constant and \(T\) is absolute temperature.

According to Wischinitzer (1998), the most important quantity of the electron gun is that of beam brightness and the maximum current density is given by:

\[
I_m = I_0 \left(1 + \frac{eV}{kT}\right) \sin^2 \alpha
\]

(4.2)

where \(I_m\) is the current density in focus electron spot, \(\alpha\) is the semi-angle of the electron beam converging on the image to form a point at the focal spot.
Lanthanum hexaboride (LaB₆) has a small work function of 2.7 eV which makes it a good candidate to be used as an electron gun. The use of LaB₆ has increased the gun brightness and greatly extended cathode life. The field emission gun is the source capable of producing the highest brightness of all. The field emission gun is a two electrode gun or diode gun made of a tip of a very sharp metal point (usually tungsten) with a radius less than 1 µm. At the metal point there is a very strong electric field of about 10⁷ V/cm and sometimes more.

The high electric field forces the electrons at the metal point and those electrons are emitted by “tunnelling” through a potential barrier. An ultra-high vacuum system (a gas pressure less than 7.5 × 10⁻⁶ – 6 × 10⁻⁶ Pa) is needed to avoid collisions between the electrons of the beam and gas molecules. Such collisions could result in a spread of electron velocities and therefore increase chromatic aberration (decrease resolution), as well as reducing the contrast of an image. It also helps to avoid high voltage breakdown (gas discharge) between anode and cathode. Another important reason why a high vacuum system is used is to minimise the interaction with a huge amount of gas and the filament. The presence of a gas such as oxygen in particular would decrease the life of the filament or damage it (Wischinitzer 1998).
Figure 4.2 Cross sectional diagram of the SEM head.

Figure 4.2 shows head of the SEM with important components. The system uses the electromagnetic and electrostatic lenses to control the path of electron beam. These lenses have no effect on the intensity of the electron beam. The basic design of an electromagnetic lens is a solenoid. The beam passes through the centre of such solenoid on its way down the column of the microscopy towards the sample. The electron beam is controlled by lenses.

The resolving power of a microscopy is directly related to the wavelength of the radiation used to form an image. The faster the electrons travel, the shorter their wavelength. Increasing energy increases resolution. The resolution voltage of the microscope is increased if the accelerating electron beam is increased. SEM produces images by detecting secondary electrons which are emitted from the surface due to excitation by the primary electron beam. The electron beam is scanned across the surface
of the sample in a raster pattern, with detectors building up an image by mapping the detected signal with beam position. Lower accelerating voltages are used to prevent beam penetration into the sample, since what is required is the generation of the secondary electrons from the surface structure of a sample.

4.2.2 ELECTRON BEAM

In scanning electron microscopy, an electron beam is scanned across a sample's surface. When the electrons strike the sample, a variety of signals are generated, and it is the detection of specific signals which produces an image or a sample's elemental composition. The three signals which provide the greatest amount of information in SEM are the secondary electrons, backscattered electrons and x-rays. Secondary electrons are emitted from the atoms occupying the top surface and produce a readily interpretable image of the surface. The contrast in the image is determined by the sample morphology. A high resolution image can be obtained because of the small diameter of the primary electron beam.

The electrons are accelerated to an energy which is usually between 1 KeV and 30 KeV in the SEM, which is lower than the energies of the TEM (100-300 keV). In SEM, the lenses serve to demagnify the stream of electrons. For example, the first condenser lens controls the amount of current in the beam and gives a fine shape to the beam. In this part, electrons with greater angles are eliminated when they are passing through the condenser aperture. The demagnification induced by the condenser lens is given by the equation:
\[ D_m = \frac{S_c}{S'_c} \]  

(4.3)

where \( D_m \) is the demagnification, \( S_c \) is the distance from the crossover point to the condenser lens and \( S'_c \) is the distance from the condenser lens to the point of focus on the other side of the lens.

The second condenser lens creates a small or fine, coherent beam. Here the diameter of the aperture can vary and more electrons with greater angles are eliminated. A set of coils help to generate a uniform magnetic field.

Backscattered electrons however arise due to elastic collisions between the nucleus of the target atom and the incoming electron. Such elastic scattering results in a negligible change or no change in energy of the scattered electrons, even though there is a change in momentum due to change in the direction of the velocity vector. The surface barrier detector is the most commonly used and it sits above the sample, below the objective lens.

4.2.3 ELECTRON PROBE

The sample has to be scanned by the electron probe in a rectangular set of straight lines known as a raster in the final lens without deflection. According to Goodhew et al (2001), the size of the electrons probe relative to the sample size is very important. If the electron probe is larger than the sample pixel, then the signal from adjacent pixel is merged, and the resolution is degraded. If the electron probe is smaller than the sample
pixel, then the signal will be weaker and noisy. For a very good performance of the SEM, the probe diameter (or sampling volume) should be adjusted to be equal to the sample pixel diameter. The interactions between the beam and the sample that last a few microseconds are registered by a detector.

4.2.4 DETECTORS

There are different types of detectors, for example the scintillator detectors that have the advantage of having a rapid response time according to Goodhew (2001), they are bulky and not suitable to detect x-rays however the solid-state detectors are usually in a thin flat plate. Such detectors do not interfere with the normal operation of the instrument but have the disadvantage of being slow. Through-the-lens detectors have a very special design objective lenses with very large magnetic fields and low spherical aberration where samples are placed within the strong magnetic field of the lens. They work with scintillator detectors and have got a very good collection efficiency of Backscattered electrons and secondary electrons and allow the microscope to work at very short distances. In some cases however, there is a severe restriction on the size and movement of the sample.

The detector counts the number of low energy secondary electrons, backscattered electrons or other radiations, given off from each point on the surface. At the same time, the resulting signal is amplified and a pixel is displayed on the cathode ray tube (CRT). Each image pixel on the display corresponds to a point on the sample, which is proportional to the signal intensity capture by the detector at a specific point.
The linear magnification is the side length of the CRT \( L \) divided by the side length \( l \) of the raster on the specimen.

\[
M = \frac{L}{l}
\]  

(4.4)

For instance, if the electron beam scanned a raster 10\( \mu \text{m} \times 10 \ \mu\text{m} \) on a sample and an image is displayed on a CRT screen 100 mm \( \times \) 100 mm, the linear magnification will be 10 000 times.

According to Rochow (1994) one of the most striking aspects of the SEM image by secondary and backscattered signal is its resemblance to images of depression and elevation illuminate. The size of the sample pixel \( p \) worked out by Goodhew \textit{et al} (2001) is given by

\[
P = \frac{100}{M} \mu\text{m}
\]  

(4.5)

where, \( M \) is the magnification.

This is the best working resolution of the SEM and it is inversely proportional to the magnification. According to Goodhew \textit{et al} (2001), no matter how good our microscope is, or how well we adjust it we cannot achieve a spatial resolution which is better than the one mentioned in (4.5) above. Therefore Goodhew (2001) defined the ultimate resolution of the SEM as being that of the smallest probe which can provide an adequate signal from the sample.
4.3 SAMPLE HOLDER

A sample holder or a sample stage is a device used to hold the sample in a desired position in the optical path. The scale on rack-and-pinion scales usually allows measurement in tenths of a millimetre. Some specialized mechanical sample holders operate with micrometre screws. All sample holders are waterproof and oil proof. They have reasonable resistant to solvent, chemicals, and heat. The plane of the main sample must be perpendicular to the axis of the microscope to achieve a good optical quality.

According to Online Catalogue for Microscope Products, there are also universal SEM sample holders (some of the sample holders are made from aluminium) on the market that can hold samples which measures 3mm to 29mm in diameter. Samples are easy to insert and remove. And also special sample holders with adapters which can load several samples at the same time (multi-holder with several stub holders).

Metallographic and other microscopes for thick samples provide movement in the z-direction. However polarizing of microscopes provides a rotatable sample holder graduated in degrees (Vernier in tenths) at the circumference. Another important use of the mechanical sample holder is during locating and recording of certain position on a sample by means of numerical coordinates x and y. To return to a position, the sample must be placed back into the mechanical sample holder in its original orientation of front versus back and left versus right. Another way of returning to a location in a sample is to mark the spot with a qualitative marker or a quantitative hardness indenter that fits into the standard thread.
4.4 TOPOGRAPHY

SEM can be used to study the topography and the chemical composition of a sample. To study the former, signals from secondary and backscattered electrons are used. When a sample is tilted, electrons are more likely to be scattered out of it. If we consider $\delta$ to be the coefficient of the secondary electrons then the variation of the electrons with the tilt of the sample is given by

$$\delta = \delta_0 \sec \theta$$  \hspace{1cm} (4.6)

where $\theta$ is the angle between the sample and the detector. It usually varies between $20^\circ$ and $40^\circ$.

The topographic images obtained are very much like images of solid objects viewed by light. These images are thus easy to interpret. It is even possible to obtain more information about the sample if stereomicroscopy is used. One can also obtain quantitative measurements from stereo pairs by determining the relative lateral displacement or parallax ($p$) of different regions of the image. The vertical height separation $h$, of two features in the image is given by

$$h = \frac{p}{2M \sin \theta}$$  \hspace{1cm} (4.7)

where $M$ is the magnification, $\theta$ is half of the tilt angle.
Backscattered electrons can also be used to get topographic images. The yield of backscattered electrons increases with an increase in the tilt angle. However in the SEM a rough surface observed with backscattered electrons will have more shadows than the same sample viewed with secondary electrons. In some cases it may be easier to interpret the image, and distinguish the peaks from the troughs in the sample than for the secondary electron image. But the sampling volume is large for the backscattered electrons and this reduces the resolution to about 0.1 µm.

Beside the surface topography, the signal from the sample provides also information about the composition of the sample. The secondary electrons coefficient does not depend very much on the composition of the sample although it may be sensitive to the surface condition and electronic structure of the material. However, according to Reimer (1998) there is a monotonically variation between the backscattered coefficient ($\eta$) and the atomic number ($Z$) of the elements in the sample:

$$\eta = -0.254 + 0.016Z - 1.86 \times 10^{-4}Z^2 + 8.3 \times 10^{-7}Z^3$$  \hspace{1cm} (4.8)

The backscattered coefficient ($\eta$) is approximately independent of the primary electron energy in the range of 5-100 keV but for $E < 5$ keV, $\eta$ decreases for high $Z$ and increases for low $Z$ with decreasing electron energy. The magnitude of the compositional or atomic number contrast from two phases of backscattered coefficient $\eta_1$ and $\eta_2$ where $\eta_1 > \eta_2$ is given by

$$C = \frac{\eta_1 - \eta_2}{\eta_1}$$  \hspace{1cm} (4.9)
It was found that the contrast from adjacent elements is quite small, typically 1% to 5% Goodhew (2001).

4.5 PHYSICAL OPERATION

Various operations require mechanical aid in controlling the $x$, $y$ and $z$ directions of moving a micro tool. Finer adjustments are provided by micrometre threads of ordinary screw-micrometres. The $x$ and $y$ movements in each unit are made possible by modified micrometre screws with control knobs attached to flexible shafts. The shafts also absorb vibrations from the operator’s hands. Clamps for holding micro tools are mounted on vertical rods for leeway adjusting to the $z$ direction. In the Emerson micromanipulator, a single vertical lever (joystick) controls a unidirectional movement in the plane of the microscopically field.

4.6 REFERENCE


https://en.wikipedia.org/wiki/Ernst_Ruska [available online: 24/1/2016]
CHAPTER 5

METHODOLOGY

5.1 INTRODUCTION

Various studies (semiconductor material hardening, MISSE, etc…) have been conducted to find the right semiconductor material in terms of its durability and its resistance against particles bombardments, heat from solar wind, reaction between the material and particles surrounding it such as ions and air particles (oxygen and argon in particular). When this happens, it affects the surface structure of the material and its thermal and electrical properties. GaSb semiconductor is identified and used in sophisticated semiconductor applications due to its suitable lattice constant of 0.61 nm, which allows it to closely match with other materials when it is grown for device fabrication.

To study the effects of the morphology and microstructure of the samples, GaSb samples were exposed samples to different treatment conditions, such as chemical etching, annealing, electron bombardment, argon gas sputtering and oxygen gas sputtering.

5.2 SAMPLE

The sample used in this study was an n-type GaSb semiconductor wafer with orientation of (100). The material parameters are tabled in table 3.2. The material was cut into 21 samples with an average dimension of 5 mm × 5 mm. The procedure followed is shown in the flow chart as shown in figure 5.1.
5.3 EXPERIMENTAL PROCEDURE

![Flow Diagram](image)

Figure 5.1: Schematic flow diagram of experimental procedure.

5.4 CLEANING PROCEDURE

The following cleaning procedure was performed. The samples were wet chemically cleaned in a boiling trichloroethane (TCE) for 3 minutes, then rinsed in boiling isopropanol for a minute and thorough rinsed in de-ionised water for 2 minutes. After that a solution of H₂O:NH₄OH:H₂O₂ in the ratio 100:3:1 was employed for chemical etching for 2 minutes. The oxide present on the GaSb was removed by immersing the sample in a solution of H₂O:HCl in the ratio 1:1 for 10 minutes then followed a thorough rinse in the de-ionised water for
2 minutes. Finally the samples were stored in methanol for 5 minutes and lastly blew dried with nitrogen gas.

5.5 ETCHING PROCESS

Etching is the process of corroding a semiconductor material using corrosive substances such as strong acids or strong bases.

Figure 5.2: Picture of etching machine.

Figure 5.2 shows similar equipment used during the etching of GaSb semiconductor material with HCl solution. The rotary etching machine was mounted on a stand which places the machine at a convenient working height. Etching solution HCl was contained in a tank at the base of the machine. It was heated by a powerful quartz heater which assures a short warm up time and constant temperature which was electronically controlled. The samples were placed in the special board carrier, the handle of which protrudes out of the machine eliminating operator contact with the etchant. The machine etches one side at a time, so only the shiny site of the samples was exposed to the etchant. In front of the etching chamber was a built in
overflow wash tank which was used for rinsing the etched boards. The spray etcher has been setup to a line resolution of 0.1 mm and etching speed of 90 seconds.

According to Zhuang and Edgar (2005) in chemical etching techniques free carrier or electrolytes are involved and the etching process is not affected by an external potential. They also added that Conventional chemical etching in aqueous solution have been widely used for defect characterisation, polarity and polytype identification and semiconductor patterning.

5.6 ANNEALING PROCESS

Annealing is a heat treatment that alters the physical and sometimes chemical properties of a material to increase its ductility and reduce its hardness, making it more wokable https://en.wikipedia.org/wiki/Annealing_(metallurgy). It involves heating a material to above its recrystallization temperature, maintaining a suitable temperature, and then cooling. In annealing, atoms migrate in the crystal lattice and the number of dislocations decreases, leading to the change in ductility and hardness. Annealing temperature is another parameter that influences the surface structure and the electrical properties of the material. Rein et al (2003) reported that by increasing the annealing temperature both crystallinity, electrical and optical properties had improved. A picture of an annealing oven is shown in the figure 5.3 below.
Generally, ovens are used for the annealing process. The inside of the oven is large enough to place the work piece in a position to receive maximum exposure to the circulating heated air. A small ceramic container was used for carrying the samples to be treated. The samples were slid to the central part of the oven where the thermocouple is placed. The samples were annealed at 300, 400, 500 and 600 °C for 20 minutes. After the annealing process, the samples were allowed to cool off before examining the surface morphology.

5.7 ELECTRON IRRADIATION PROCESS

The samples were irradiated by 10 keV electron beam accelerator in high vacuum. The current density was set to 100 nm/cm² for irradiation. The fluency of the 10 keV electron beam was $2 \times 10^{14}$ e/cm² at room temperature. According to Watt et al (2005) the primary interaction in the irradiation process is the electron/electron collision. This gives a large angle multiple scattering of the electron beam leading to the classic “Pear shaped” ionisation
volume around the entry point into the material. Palmlof and Hjierberg (2000) reported that a
dramatic response in his study of the polymer using a smaller electron beam irradiation dose
which according to He and Gu (2003), is needed to obtain a certain degree to crosslinking.
After electron irradiation, samples surfaces were analysed by SEM.

5.8 OXYGEN SPUTTERING PROCESS

The technique of sputtering with oxygen gas at high oxygen pressures (1×10² - 4×10² Pa)
allows a smart and homogeneous thin film formed due to negatively charged oxygen ions. If
conventional sputtering pressures of about 0.01 mbar are used for the on-axis deposition of
film, the negatively charged oxygen ions were accelerated towards the samples by the bias
potential. With the high oxygen pressure sputtering technique, usually the problem is solved
by multiple scattering of the oxygen ions at background gas pressures above 1 mbar with
subsequent reduction of their kinetic energy down to thermal energies before they reach the
samples.

![Figure 5.4: Typical sample oxidation furnace.](https://www.mems-exchange.org/MEMS/processes/)
Figure 5.4 shows the oxidation furnace. The samples were exposed to oxygen at approximately 1000 °C. This is called dry oxidation. After the setup temperature has been reached, samples were placed into the quartz boat and placed into the tube utilizing a furnace loader. During heating pure oxygen gas flows through the processing tube. After an hour, samples were unloaded from the furnace and allowed to cool.

5.9 ARGON SPUTTERING PROCESS

When argon (Ar) particles interact with target material, atoms and ions were ejected from the surface of the material. In the process electrons were ejected and they kept the plasma going. The argon ions (Ar⁺) were reflected as argon neutrals and they were buried into the target material. There was transfer of momentum from the argon ions to the target atoms which were in the gas phase.

![Diagram for argon sputtering](http://www.uccs.edu/~tchriste/courses/PHYS549/549lectures/sputter.html)

The argon pressure was set to a maximum of 100 mTorr with the aim increasing the number of argon ions without increasing the number of argon neutrals. The applied voltage was between -2 to -5 keV. The sample temperature was controlled by the applied voltage. When the applied voltage was increased the sample temperature was increasing.
5.10 IMAGE REQUISITION

In this study, Scanning Electron Microscopy was used to analyse the samples. The following setup parameters were applied for all samples: power of 43 W and resolution of 1 μm.

5.10.1 SETUP OF THE SYSTEM

All samples with SEM were processed first in order to produce a suitable image. This was mainly because the inside of the system was always under high vacuum in order to enable the electron beam to travel in straight line. In this study the vacuum of $10^{-8}$ mbar was reached. Figure 5.6 depicts the diagram of the scanning electron microscope.

![Diagram of the Scanning Electron Microscope (SEM) head component.](https://www.purdue.edu/ehps/rem/rs/graphics/sem2.gif)

**Figure 5.6**: Diagram of the Scanning Electron Microscope (SEM) head component. https://www.purdue.edu/ehps/rem/rs/graphics/sem2.gif
5.10.2 SAMPLE PREPARATION

Samples were prepared before being placed or loaded in the SEM. This is due to the fact that SEM operates under vacuum conditions and to allow electrons to form images. The following were done: removal of all waters from the sample to avoid vaporisation of waters during operations, this was done at temperature higher than the boiling point of water. Then samples were coated with gold material deposited by low vacuum coating. This was done to prevent charging of the samples which would occur because of the accumulation of static electric fields and also due to the electron irradiation during imaging. It also increases the amount of secondary electrons that can be detected from the surface of the sample.

Izyumskaya et al (2007) recommend that all non-metals need to be made conductive by covering the sample with a thin layer of conductive material. This is done by using a device called a "sputter coater." The sputter coater uses an electric field and argon gas. Samples were placed in a small chamber within a vacuum. Electric field caused a removal of an electron from argon, making the atoms positively charged. Then argon ions became attracted to a negatively charged gold foil. The argon ions knocked gold atoms from the surface of the gold foil. Thus making gold atoms to fall and settle onto the surface of the sample producing a thin gold coating.

5.10.3 LOADING THE SAMPLE

A sample holder was used to hold the sample in a desired position within the optical path. Graduations plus their Vernier scale on rack–and-pinion scales were used for measurement.
The mechanical sample holder was operated with micrometre screws. It is recommended that sample holders should be waterproof and oil proof. They should be reasonable resistant to solvent, chemicals, and heat (Rochow and Tucker 1994). The planes of all samples were placed perpendicular to the axis of the microscope in order to achieve a good optical quality.

Another important use of the mechanical sample holder is in locating and recording a certain position on a sample by means of numerical coordinates $x$ and $y$. To return to a position, the sample were put back into the mechanical sample holder in its original orientation of front versus back and left versus right. Another way for returning to a location in a sample was to mark the spot with a qualitative marker that fits into the standard thread.

5.10.4 SAMPLE SCANNING

Data was acquired pixel by pixel, and line by line. The electrons were accelerated to an energy of 4.9 keV in the SEM. Samples were scanned by the electron probe in a rectangular set of straight lines in the final lens.

5.11 REFERENCES


CHAPTER 6
RESULTS AND DISCUSSION

6.1 INTRODUCTION

In this study, we report the SEM investigations of the microstructural properties of GaSb semiconductor. The main objective of the work was to investigate the effect of various external treatments on the morphology of the semiconductor material.

6.2 CONTROL SAMPLE

Figure 6.1 shows SEM micrograph of the surface of GaSb. The sample was not exposed to any treatment.

![Microscopic image of GaSb control sample.](image)

**Figure 6.1** Microscopic image of GaSb control sample.
Inspecting the surface has led to an indefinite picture of the layer structure. The images display a plate-like crystalline texture with domains on the micrometer scale. This shows a pores structure.

6.3 EXPERIMENTAL SAMPLES

6.3.1 ANNEALING

Figure 6.2 shows four samples which were annealed at various temperatures. Sample $A$, $B$, $C$ and $D$ were annealed at 300, 400, 500 and 600 °C respectively. The matrix of figure 6.2 $A$ showed a lot of small holes with a very few isolated big holes. As the temperature increased from $A$ to $B$ the surface roughness increased. The density of big holes has increased at the expense of small holes. This was due to the coalescence of holes to form bigger holes. In figure 6.2 $C$ we observed a significant number of big holes as well as an increase in the surface roughness. In figure 6.2 $D$ we observed the beginning of open boundaries and the filling up of small holes as the particles kept on migrating under the influence of temperature. All the samples exhibited rough surface with an increasing roughness as the temperature compare to the control sample which was smoother. At 500 °C and 600 °C, the annealing temperature was found to have a profound effect on the size of the hole, with a significant increase at higher temperatures.
Figure 6.2 Microscopic surface images of GaSb after annealing.

Figure 6.3 below shows the dependence of hole size on annealing temperature. The hole size exhibits a well defined behaviour as a function of temperature, rising by a factor of 0.39 as the temperature is raised from 300 °C to 600 °C. For temperatures between 300 °C and 400 °C, 400 °C to 500 °C and 500 °C to 600 °C the factors by which the hole size have increased were 0.19, 0.11 and 0.09 respectively. The factor of increase decreased as the temperature increased.
Figure 6.3 Rising factor as a function of annealing temperature.

We believe that this increase is due to increasing mobility of atoms on the surface with increasing annealing temperature. At low temperature, the sample surface was fairly smooth, however the surface roughness increased dramatically with increasing annealing temperature.

6.3.2 CHEMICAL ETCHING

Chemical etching treatment was employed with HCl at room temperature for 5, 10, 15 and 20 minutes. All samples were examined with SEM.
Figure 6.4 Microscopic surface images of GaSb after etching with HCl.

The effect of the etching treatment time on the GaSb samples is shown in figure 6.4. The treatment time was 5, 10, 15 and 20 minutes for sample A, B, C and D respectively. The etched surfaces were observed under scanning electron microscopy. All etched surfaces produced significantly rougher surface than the control sample. The SEM micrographs suggest that the etching treatment time has an important effect on the morphology of GaSb semiconductor material.

The increase of the size of the pores were noted when the treatment time was increased from 5 minutes to 20 minutes. Typical pore diameter values obtained with an etching treatment time of 15 and 20 minutes were approximately 32 nm and 44 nm, respectively. Similar study was conducted by Erdoga et al (2012), where various etching solution were compared. The
diameter of the pores was observed to increase from 35 nm to 60 nm for 30 and 60 minutes treatment time, respectively.

In figure 6.4 D, more holes have merged to produce deeper valleys as compared to sample 6.4 C. These are areas were films are removed leaving holes. More valleys are shown due to removal of films and subsequent merging of holes and islands to form valleys. Those open boundaries give a columnar morphology to the sample.

In other samples (A, B and C) as the etching process continues the density of bigger holes has increased but there was no significant change in surface roughness. The sample became also faceted.
6.3.3 ARGON SPUTTERING

Figure 6.5 Microscopic surface images of GaSb after bombardment with argon gas.

Argon gas has been deposited at a constant flux with different times varying from 5 min to 20 min. The SEM images of the argon bombardment show an increase in the number of holes as well as the size of the holes from A to B. In figure 6.5 A there was no significant change in the morphology of the sample. This was due to the fact that the atom surface diffusion was insufficient to overcome the geometrical shadowing by the surface features. In sample B we had two open boundaries which had separated the sample in three areas. The in-equivalence of the areas could be seen as a manifestation of strain and the influence of the substrate onto the film surface. The area on the left hand side had a greater density of holes and bigger
holes’ size than the two other areas. The density and the size of the holes decreased as we moving from left to right.

The coating had a fibrous structure and looks like a transitional phase between samples B and C. It also appeared that the atom surface diffusion is from right to left in B. That is why the surface roughness also decreased from left to right for sample B. As the fluency increased and particles with high energy reached the surface of the sample C, these particles eroded the peaks and filled in the valleys (the open boundaries between the areas) to some extent. There was an increase in the grain size and the surface was faceted. In sample D the grain size has decreased and the surface topology was much smoother with some isolated shallow valleys. This may be because bulk diffusion has allowed re-crystallisation.
6.3.4 OXYGEN GAS

SEM images of the surface evolution after bombardment with oxygen gas show an increase in the size of the holes as the fluency increases. Figure 6.6 shows samples A, B, C and D after being exposed to various oxygen fluxes at constant time. In sample A there is no significant change in the surface morphology of the material. This was because at that point the atom diffusion was insufficient to change the structure of the material. However in sample B we notice the presence of more holes and a deep valley. In sample C the size of the holes has increased but there was a decrease in the number of holes. Initially at low fluencies the density of the holes increases until they merge to form bigger holes. As they merge the
density of the holes drop off. The valley has become shallower and the feature of the surface appeared faceted.

In sample $D$, there were several domains; the top has become smoother with very few isolated small holes. In this part it looks like re-crystallisation has taken place. However in the middle there is still some big holes. The surface roughness increases as more oxygen particles strike the surface of the sample. At the bottom of the sample there are more holes compared to the top area of the sample. This can be a demonstration that oxidation has started at the top due to bulk diffusion. Moreover such diffusion has allowed re-crystallisation and densification.

### 6.3.5 ELECTRON BOMBARDMENT

The electron bombardment was carried out with varying sputter time from 40 s to 4000 s to follow the morphology over a wide range of depths. Figure 6.7 below shows samples after irradiated with electron fluency of $2 \times 10^{14}$ e/cm$^2$ at room temperature. In sample $D$ we observe a non-uniform surface on which notice the presence of big holes, large and deep valleys and precipitates in some areas. In sample $B$ as more electrons reach the sample the density of holes decreases and larger and longer valleys are formed. Inside the valleys there are some dislocations.
In figure 6.7 A we observe a non-uniform surface on which we notice the presence of big holes, large and deep valleys and precipitates in some areas. In figure 6.7 B as more electrons reach the sample the density of holes decreases and larger and longer valleys are formed. Inside the long valleys there are some dislocations. This was because of the high energy electrons arriving at the sample which increased the atom surface mobility. This caused the coalescence of islands which leads to the formation of columnar morphology observed in figure 6.7 B and figure 6.7 D when the coalescence was imperfect. In figure 6.7 C the surface became more homogeneous than in figure 6.7 B and figure 6.7 D, showing that the columnar morphology was a transitional phase between figure 6.7 A and figure 6.7 C during which particles were migrating. We believe
that it was due to the filling up of the open boundaries and islands due to the perfect coalescence of the islands as the particles flux was increased. This was in agreement with the findings of Knights et al (1979). The ratio of bigger holes to smaller holes has decreased significantly at that stage. In figure 6.7 D we observed another intermediate stage but this with shallower open boundaries as compared to figure 6.7 B.

6.4 REFERENCE


THOMAS R, MOCHIZUKI S, MIHARA T and ISHIDA T (2002) Effects of PbTiO$_3$ seed layer on the characteristic of rf-sputtered Pb(Zr$_{0.5}$,Ti$_{0.5}$)O$_3$ thin films, Int. Ferroelectrics (46) 95.

CHAPTER 7
CONCLUSION

7.1 INTRODUCTION

GaSb semiconductor material has been prepared successfully before being exposed to various treatment conditions. The surface morphology was examined by using SEM equipment. The crystal quality of GaSb was strongly affected by treatment conditions.

7.2 ANNEALING

annealing temperature was found to have a profound effect on the hole (pits) size, with a significant increase at higher temperatures. As the temperature was increased, the surface morphology was observed to change.

7.3 CHEMICAL ETCHING

The chemical etching treatment had an impact on the morphological structure of GaSb semiconductor material (increasing the etching treatment time was found to be favourable). At low concentration some dislocations were observed which was different for higher concentration.
7.4 ARGON SPUTTERING

The morphology of the surface after argon sputtering reflects the poor quality surface. This is essentially due to the wetting problem leading to discontinuous of a number of islands. With decreasing the argon flux, the quality improves.

7.5 OXYGEN GAS

The drop in the concentration of oxygen in the sample indicates a creation of oxygen vacancies. This drop cannot be explained as the improvement on the material properties.

7.6 ELECTRON BOMARDMENT

The mean width and depth of the created holes (pits) were about 1.6 µm and 1.4 nm, respectively. More damage was caused by electron flux.

7.7 CONCLUSION

Various treatments, annealing, chemical etching, oxygen deposition, argon sputtering and electron bombardment of GaSb have been conducted. The results revealed that electron bombardment has severe effect on the surface structure of GaSb with rougher surface and larger open boundaries than any other treatment. It was followed by annealing which has exhibited some big holes and shorter valleys at our temperature range. The samples treated with oxygen had lesser big holes compared with the one annealed. However the two treatments have a lot of similarities. Chemical etching and argon sputtering have some similarities; their surfaces first became rougher before becoming smoother. However the
samples treated by argon sputtering have rougher surfaces compared with the one of chemical etching.

All the treatments have caused profound damage to the morphology of the samples. This is evidence that the GaSb material will not sustain the harsh conditions to which it will be exposed in space. For space deployment, the GaSb material needs to be hardened. The material can be manufactured on insulator substrate such as SiO$_2$ or shielded by the use of depleted boron (consisting of isotope boron-11) in the borophosphosilicate glass passivation layer protecting the GaSb sample, as boron boron-10 readily capture neutron and undergoes alpha-decay (https://en.wikipedia.org/wiki/Radiation_hardening). All those design techniques can reduce radiation damage but cannot stop it. Therefore the goal of radiation-hard design is not so much to obtain a system whose characteristics do not change under irradiation, rather than to maintain the required performance characteristics over the lifetime of the system http://www-physics.lbl.gov/~spieler/radiation_effects/rad_tutor.pdf

7.8 RECOMMENDATION

The roughness surfaces with dimensional island like features and holes (pits) were observed on the surface of GaSb samples with SEM after treated with different conditions. The study recommends that the semiconductor material be treated before being used under certain conditions to improve the favorable conditions for devices on the material.

7.9 REFERENCES

http://www-physics.lbl.gov/~spieler/radiation_effects/rad_tutor.pdf [available online on 24/1/16]
APPENDICES

APPENDIX A: LIST OF TABLES

Table 3.1 Properties of some commonly used semiconductor materials. 28
Table 3.2 Basic properties of GaSb 31

APPENDIX B: LIST OF FIGURES

Figure 3.1 The (atomic) crystal structure of GaSb. 31
Figure 4.1 Picture of Scanning electron microscopy. 38
Figure 4.2 Cross sectional diagram of the SEM head. 41
Figure 5.1 Schematic flow diagram of experimental procedure. 52
Figure 5.2 Picture of etching machine. 53
Figure 5.3 Diagram for annealing Oven. 55
Figure 5.4 Typical sample oxidation furnace. 56
Figure 5.5 Diagram for argon sputtering. 57
Figure 5.6 Diagram of the Scanning Electron Microscope (SEM) head components. 58
Figure 6.1 Microscopic image of GaSb control sample. 62
Figure 6.2 Microscopic surface images of GaSb after annealing. 64
Figure 6.3 Rising factors as a function of annealing temperature. 65
Figure 6.4 Microscopic surface images of GaSb after etching. 66
Figure 6.5 Microscopic surface images of GaSb after bombardment with argon gas. 68
Figure 6.6 Microscopic surface images of GaSb after bombardment with oxygen gas. 70
Figure 6.7 Microscopic surface images of GaSb after bombardment with electron beam. 72